Offshore stereo measurements of gravity waves: classical epipolar and novel variational techniques

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Outline

- Motivation
- Prior vision-based systems for wave measurement
- Two main classes of techniques:
  - Epipolar techniques
  - Variational methods
    - Incorporate physics of the waves
    - Simultaneous reconstruction of snapshots
- Examples
- Conclusions

Motivation

- Topic: measurements of ocean waves using vision systems.
- Applications:
  - Monitoring of sea states
  - Improvement in the design of platforms
  - Study of turbulence and wave mechanics
  - Validation of physical models of the ocean
- Interdisciplinary work:

  ocean engineering and computer vision

Literature review

- Stereography and vision applied to ocean engineering:
  - First experiments: cameras mounted on a ship (Schumacher, 1939).
  - Long-wave sea topography (SWOP) (Coté et al. 1960).
  - Directional measurement of short ocean waves (Shemdin et al. 1988, 1992).

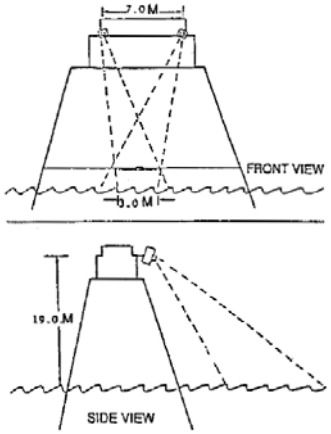


Figure 1. Schematic of Stereo Geometry Used in the Chesapeake Light Tower Experiment.

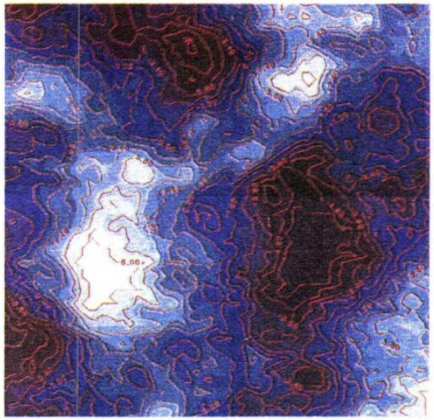


PLATE 1. Example contour map of ocean surface elevation. The surface area covered is 4.1 m by 4.1 m. The elevation contours are in cm.

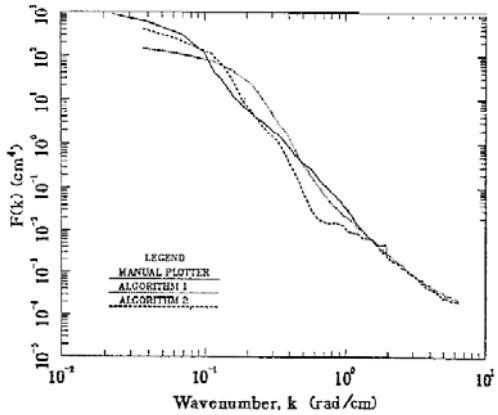
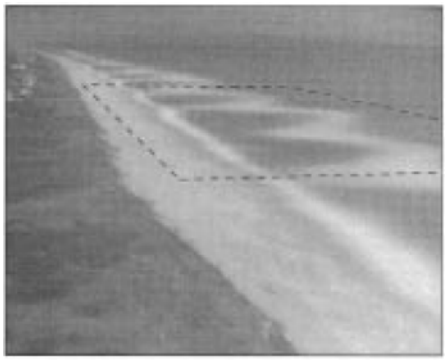


Figure 3. Comparison of Omni-Directional Spectra Using Two Digital Stereo-Correlation Algorithms and the Stereo Plotter Method.

Literature review

- Nearshore Oceanographic Field Studies (Holland et al. 1997)



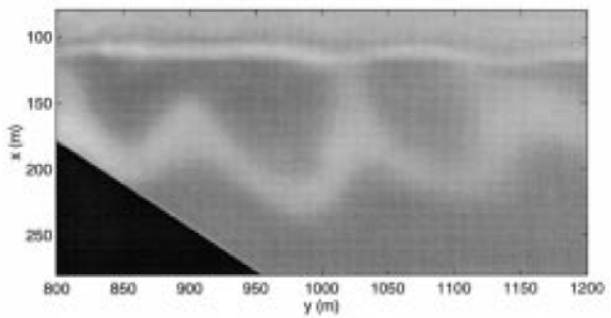
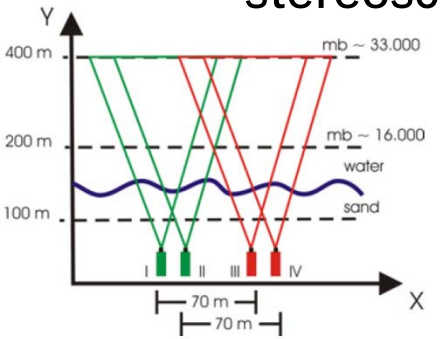
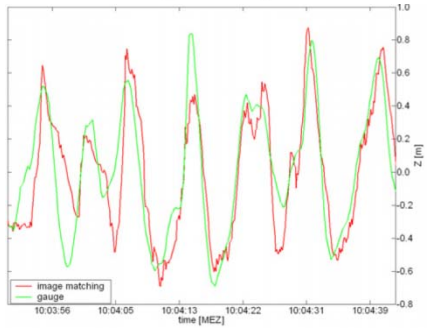


Fig. 5. Ten-minute time exposure images of wave-breaking patterns at Duck,

- WaveScan project (Santel et al. 2004):
  stereoscopic 3d-image sequence analysis of sea surfaces.





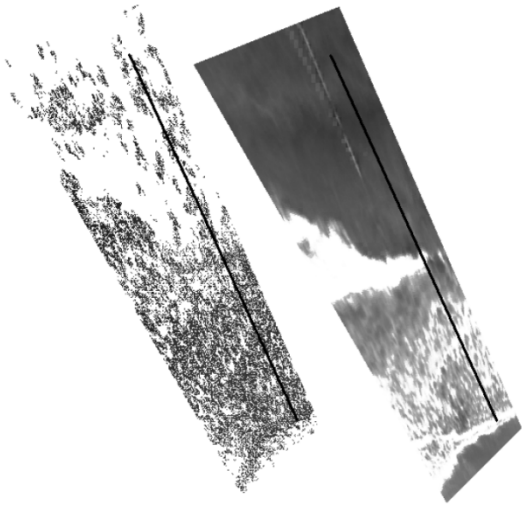


Figure 4. Correlated points and associated orthophoto

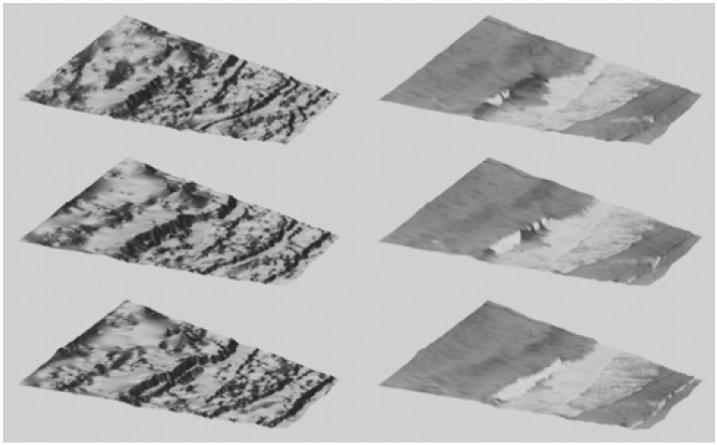
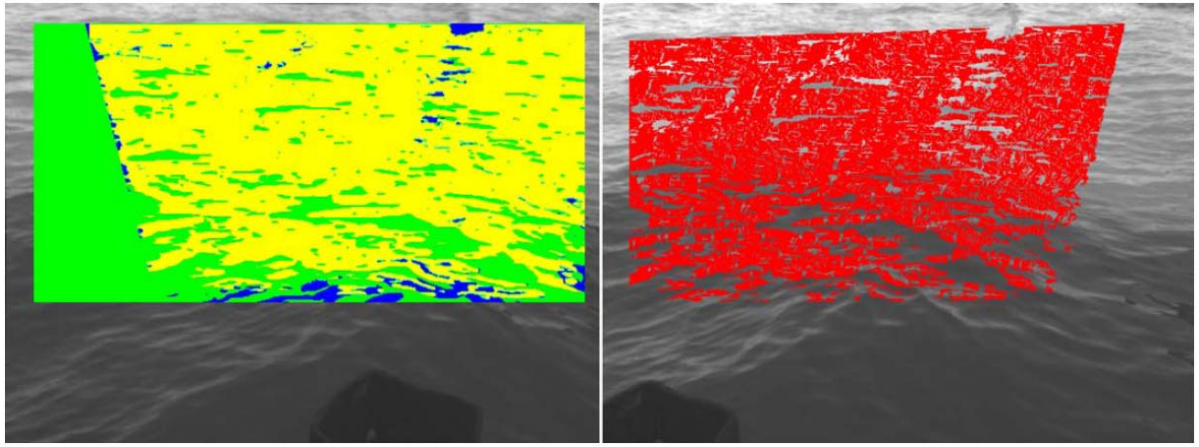
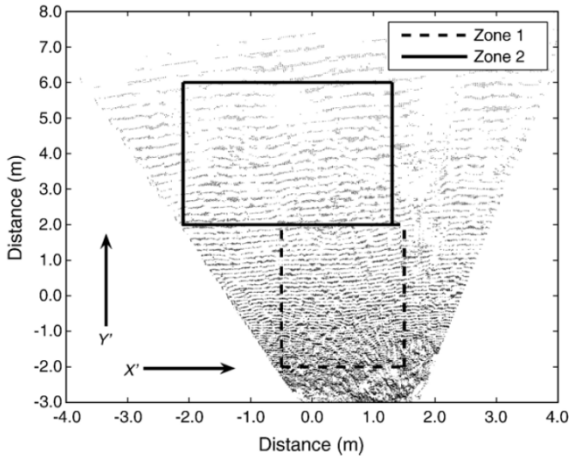
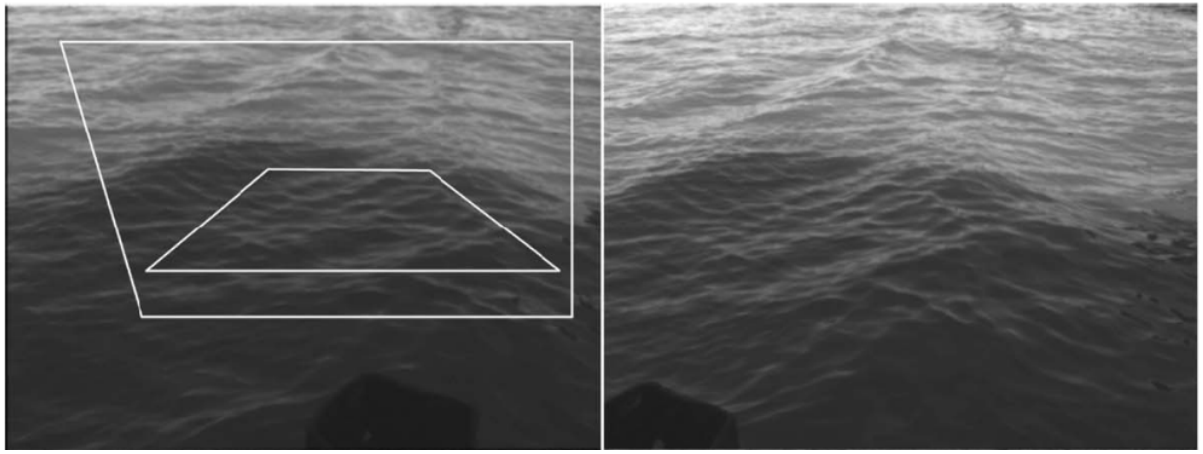


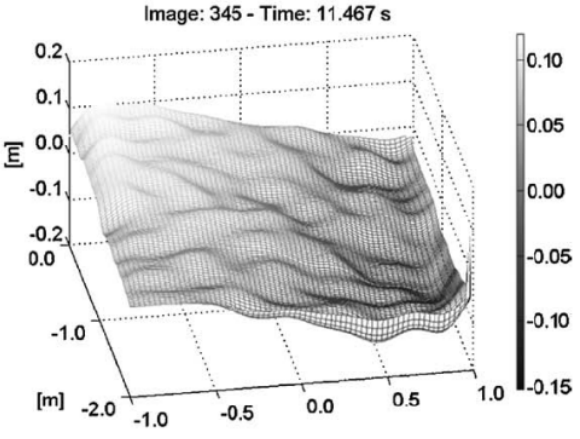
Figure 6. Sequence of water surfaces with $\Delta t = 1$ s
left: surface models; right: with overlaid orthophotos

Literature review (Benetazzo, 2006)



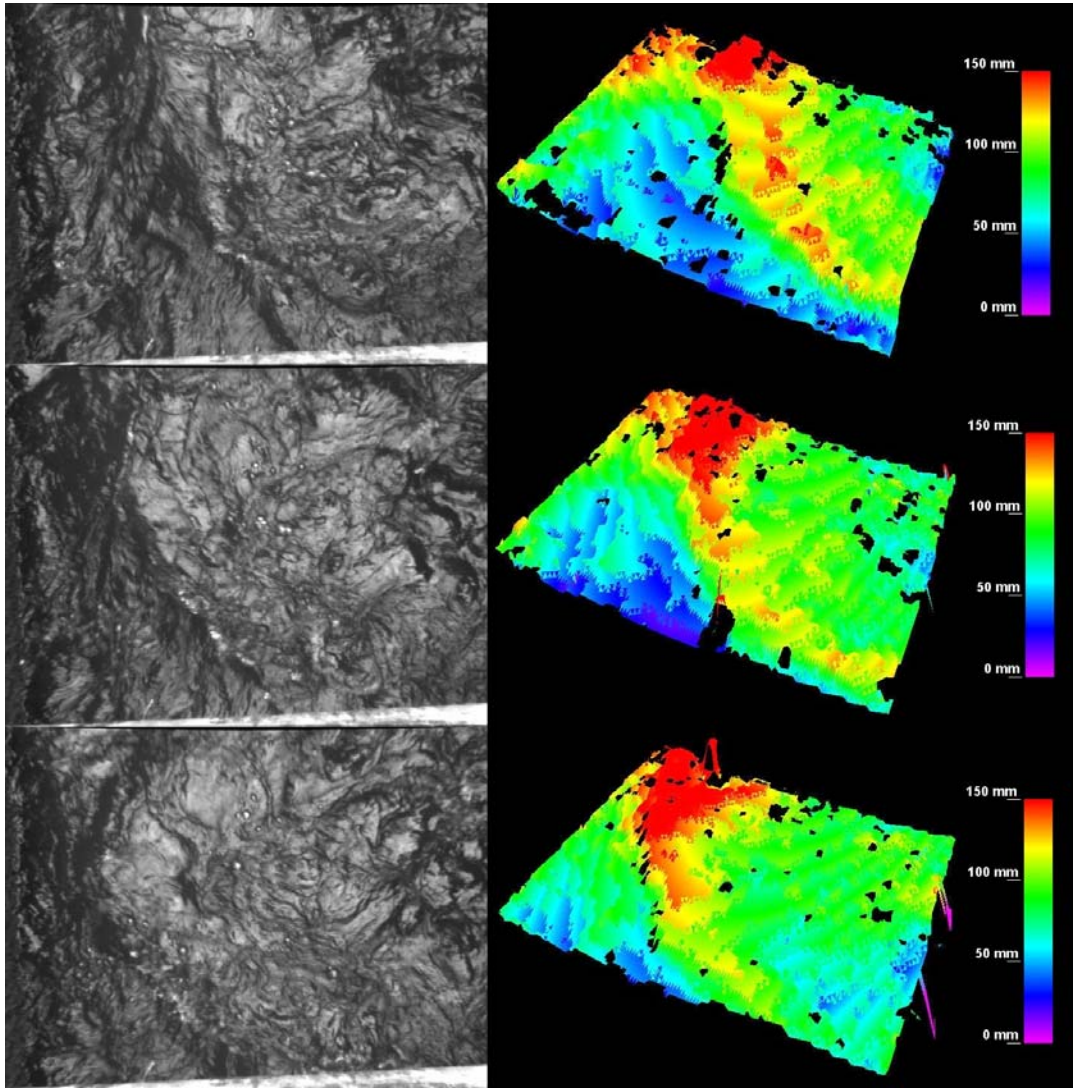






Literature review (Benetazzo, 2006)

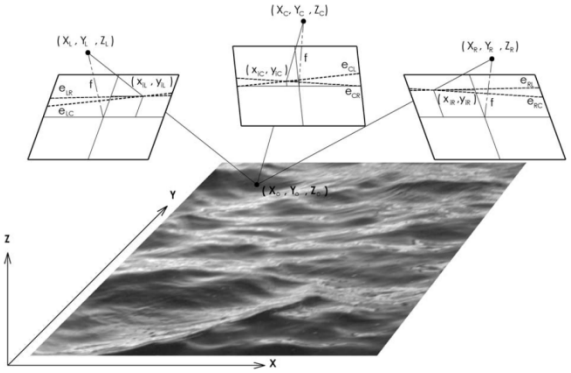
Water surface elevation in *time*:
from 2D image sequences to 3D map sequences

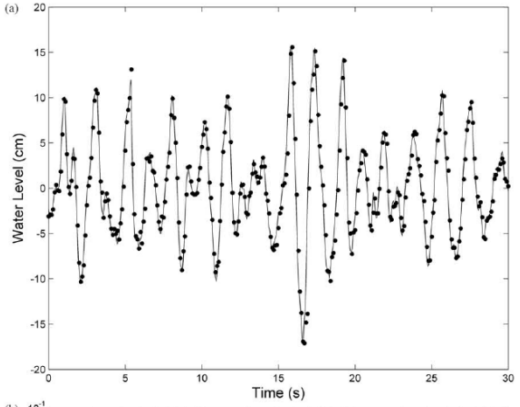


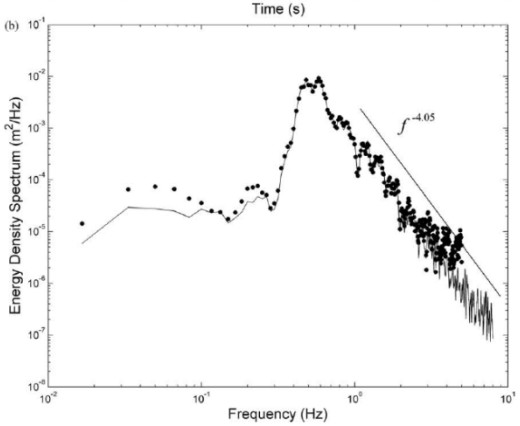
- Z_0 ~ 1.70 m, b = 0.22 m
- Matched Area : 0.94 x 0.78 m^2
- e_{rx} = e_{ry}= 0.15 cm, e_{rz} = 0.69 cm
- 90 % of points matched
- 480 x 640 pixel camera
- F = 6.3 mm, ss=1/200 s

Literature review. ATSIS

- Automatic Trinocular Stereo Imaging System (ATSIS) (Wanek and Wu, 2006).
- Measurement and analysis of ocean wave fields in 4D (MacHutchon and Liu, 2007, 2009).
- Virtual wave gauges for measuring surface wave characteristics (Bechle and Wu, 2011).







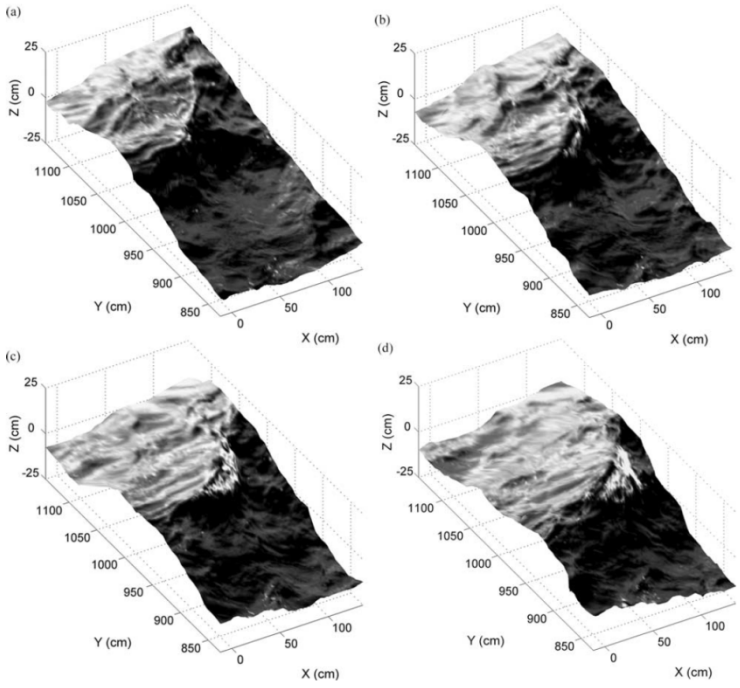
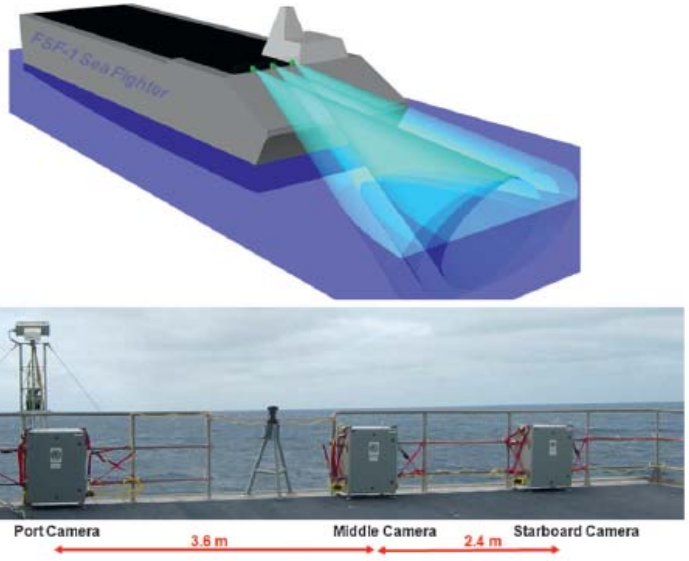
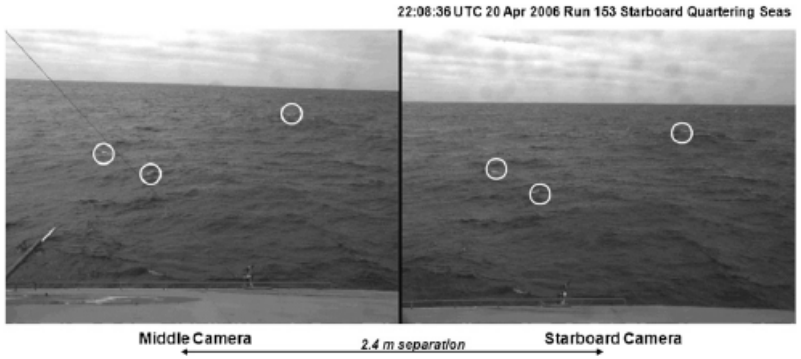


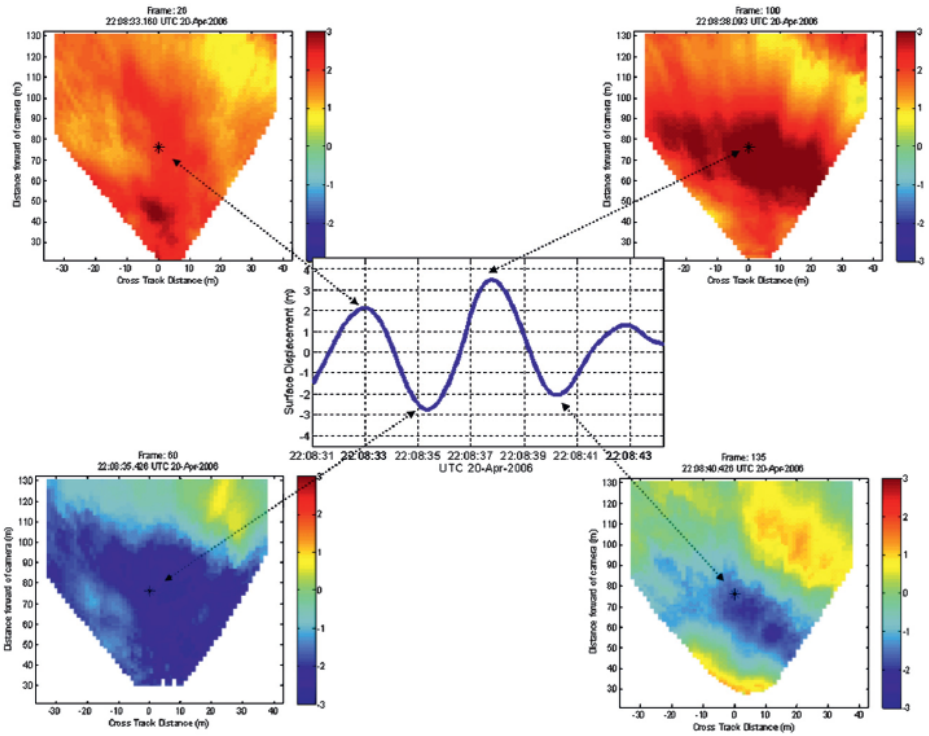
Fig. 9. A temporal evolution of a three dimensional wave breaking event at (a) $t=0.0$ s, (b) $t=0.1$ s, (c) $t=0.2$ s, (d) $t=0.3$ s, (e) $t=0.4$ s, and (f) $t=0.5$ s.

Literature review. More stereo systems

- Three-Dimensional Imaging of the High Sea-State Wave Field encompassing ship slamming events (Brandt et al 2010).

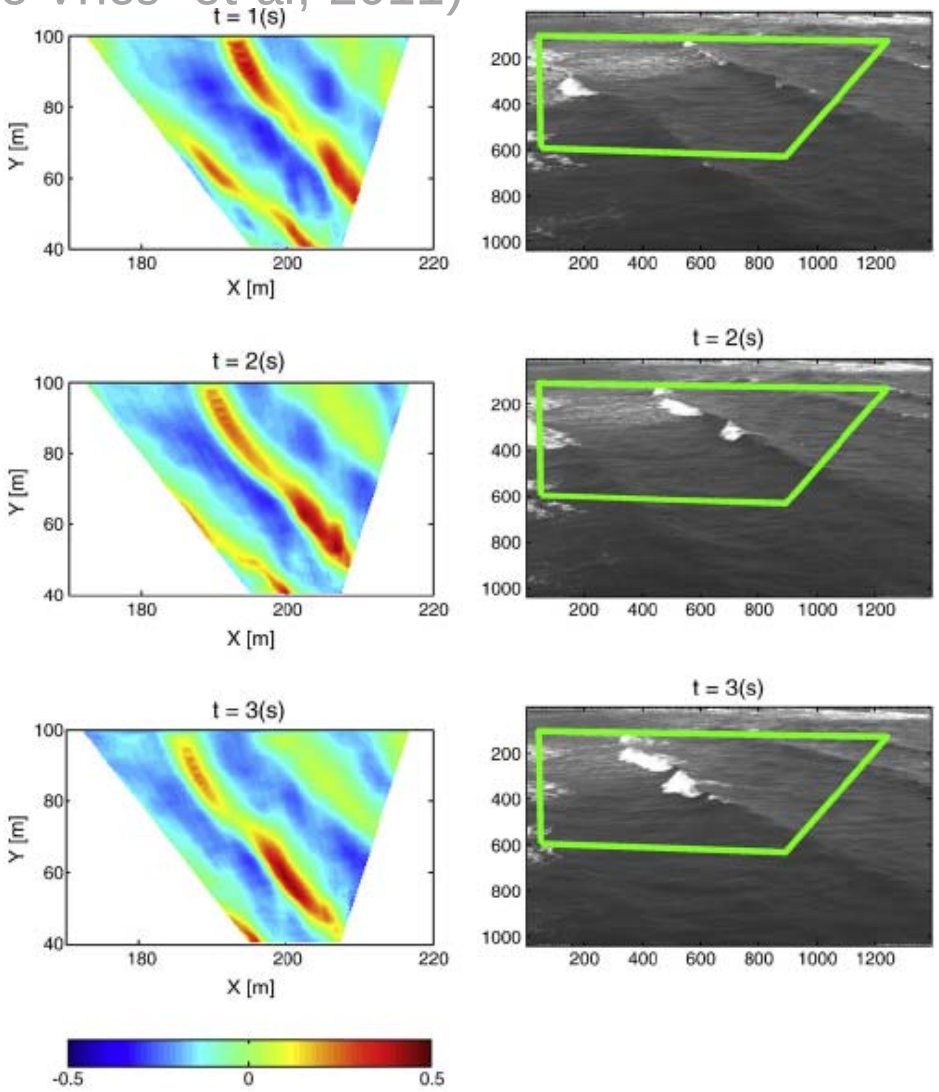






Literature review. More stereo systems

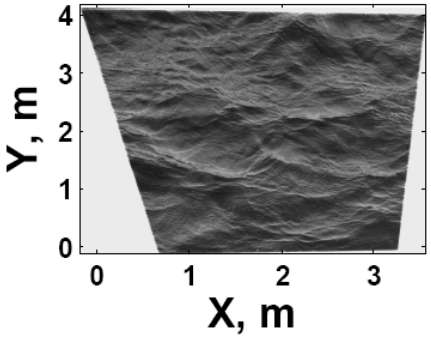
- Remote sensing of surf zone waves using stereo imaging (S. de Vries et al, 2011)

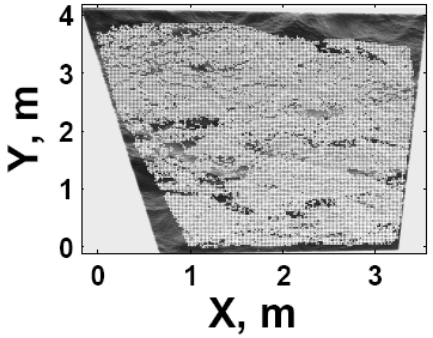


Also in WISE 2012

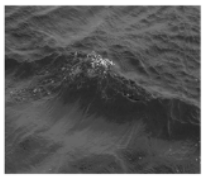
- Extraction of short wind wave spectra from stereo images (Kosnic and Dulov, 2011).
- Statistical characterization of short wind waves (Mironov, Kosnik, Dulov, Hauser, Guérin, 2012?).

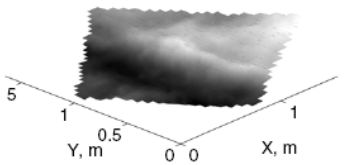
Problem: gaps (holes) in reconstructed surface



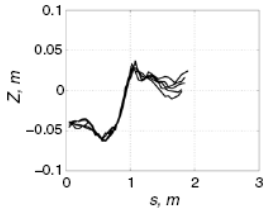


Sample reconstrunctions:

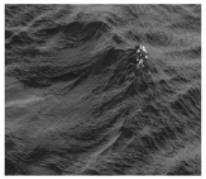

(d)

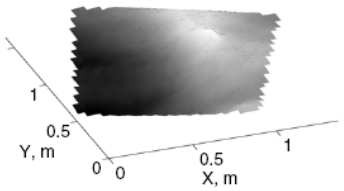


(e)

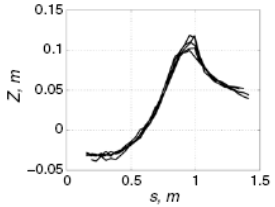


(f)


(g)

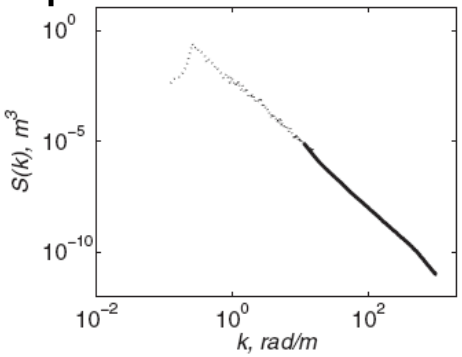


(h)



(i)

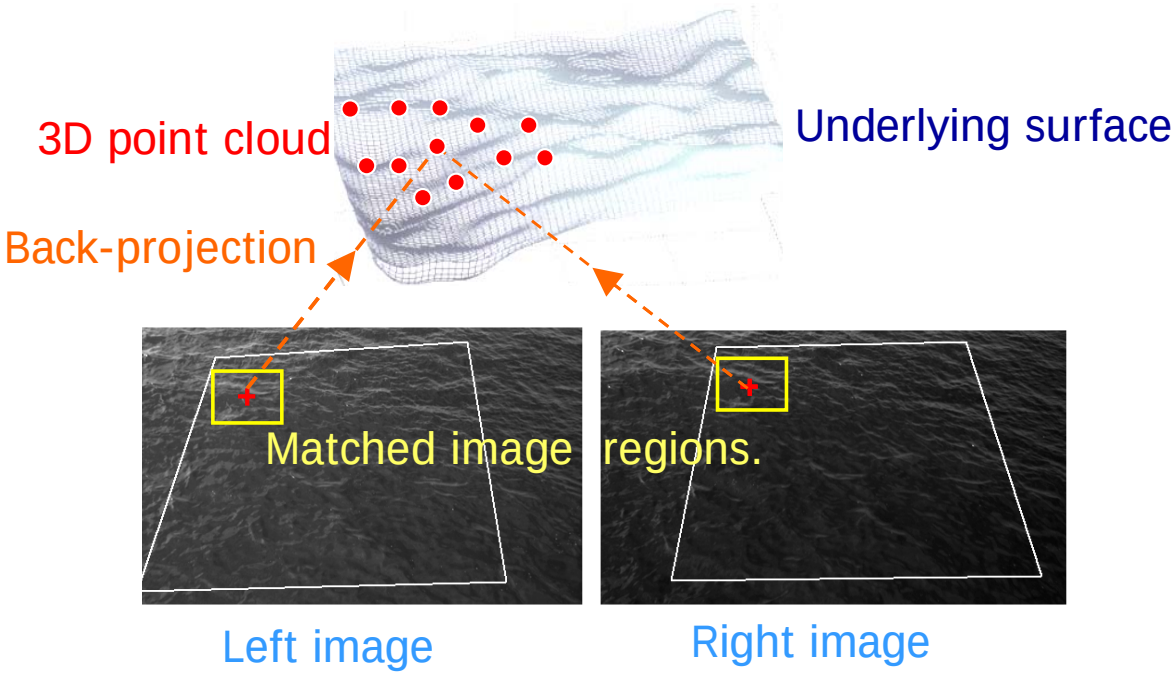
Spectrum

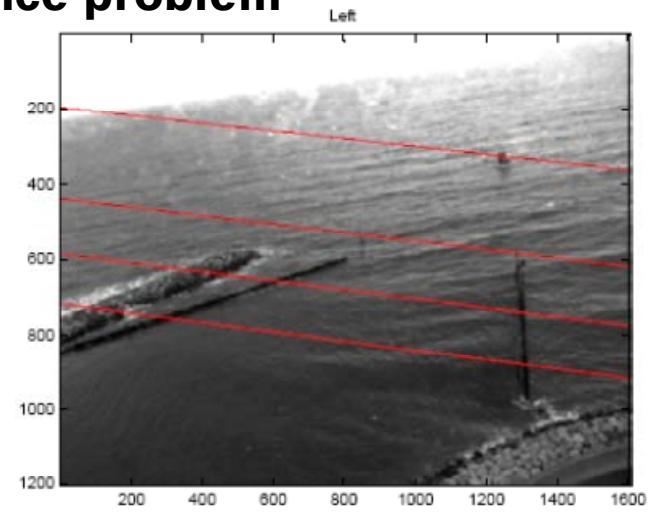


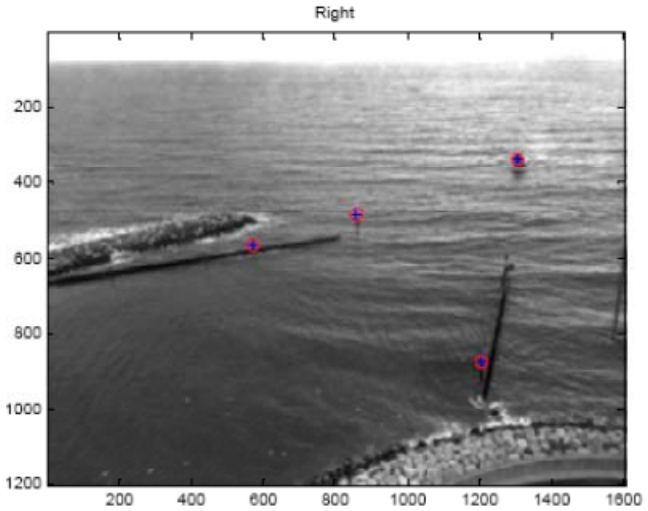
3-D reconstruction of the water surface from images

Epipolar stereo solution (Image-based methods)

Philosophy: separate the matching/correspondence problem from the reconstruction problem

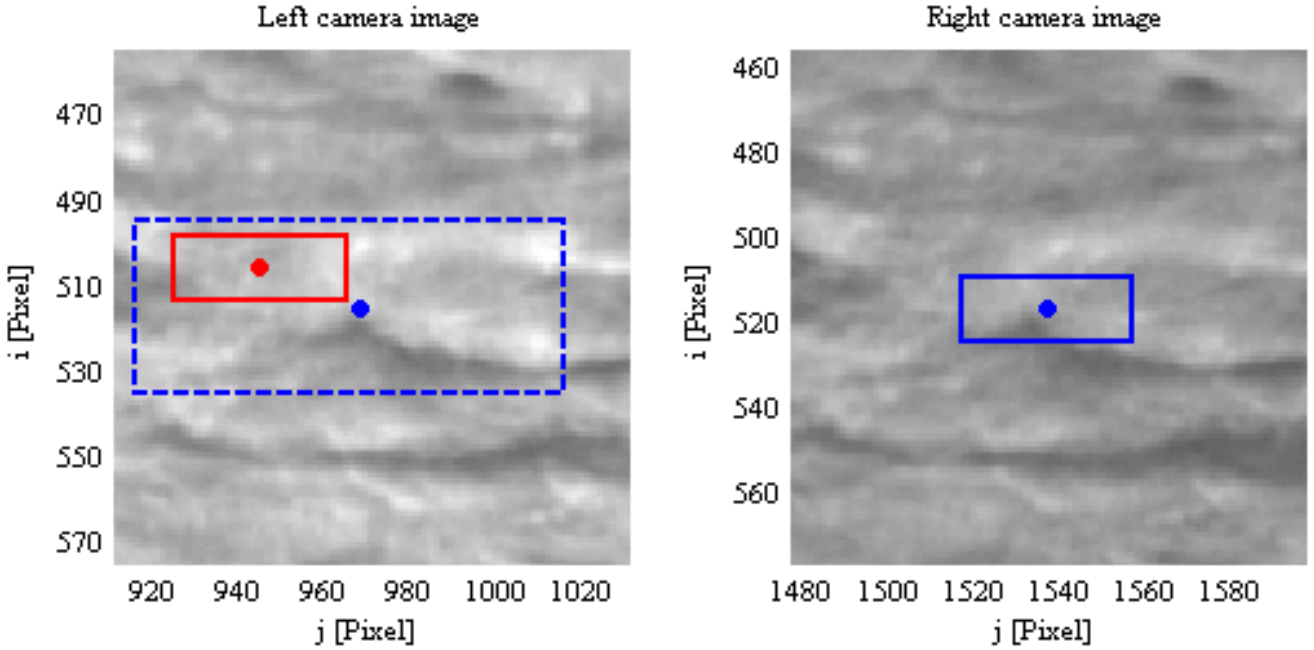




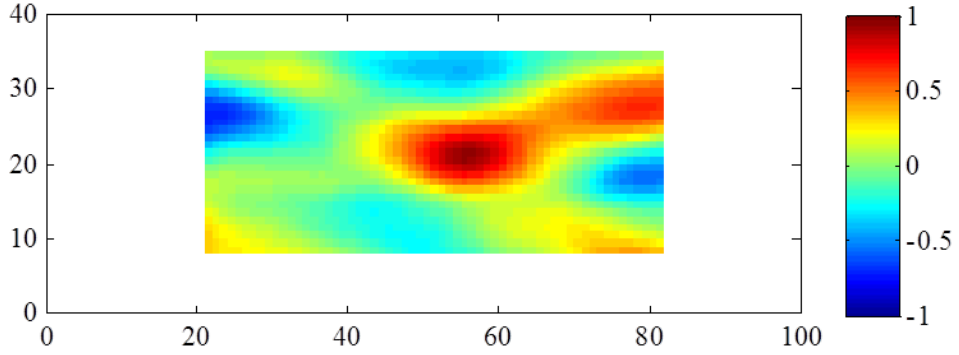


Epipolar method. Feature matching

Case of horizontal epipolar lines



Photometric matching score: correlation of intensities



Epipolar method. Surface as a collection of points

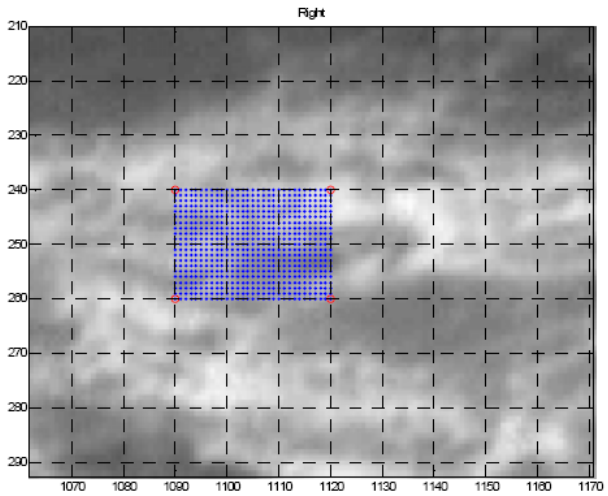


Image 1

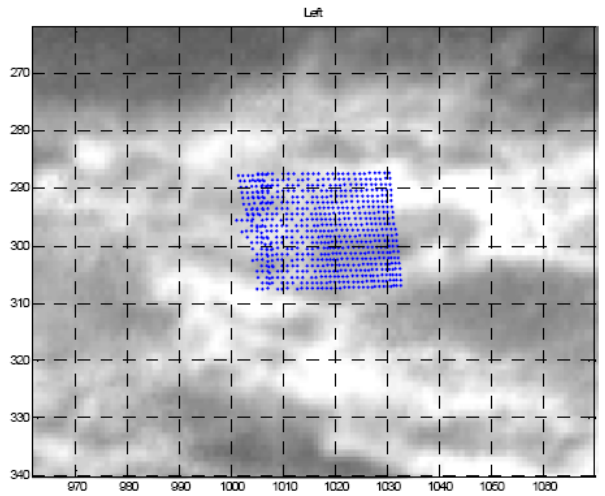
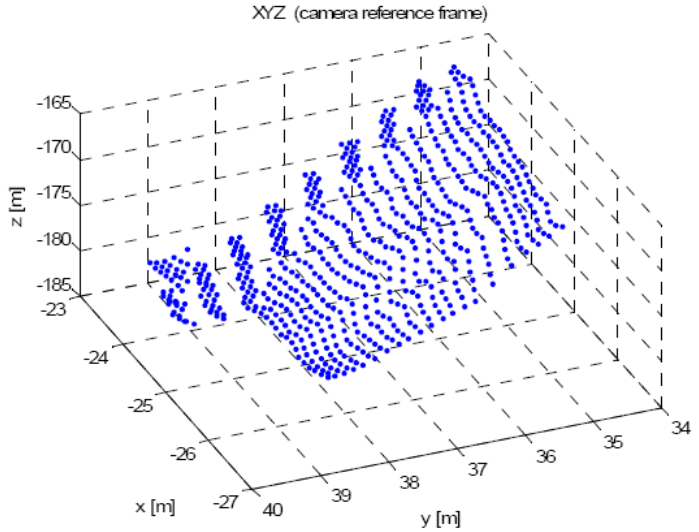
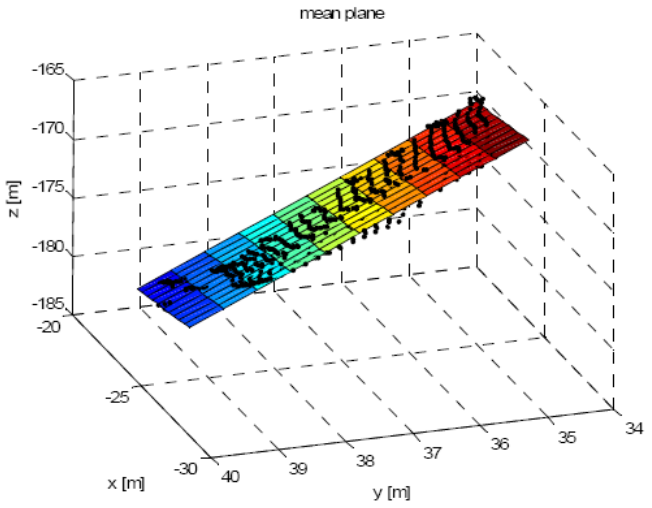


Image 2

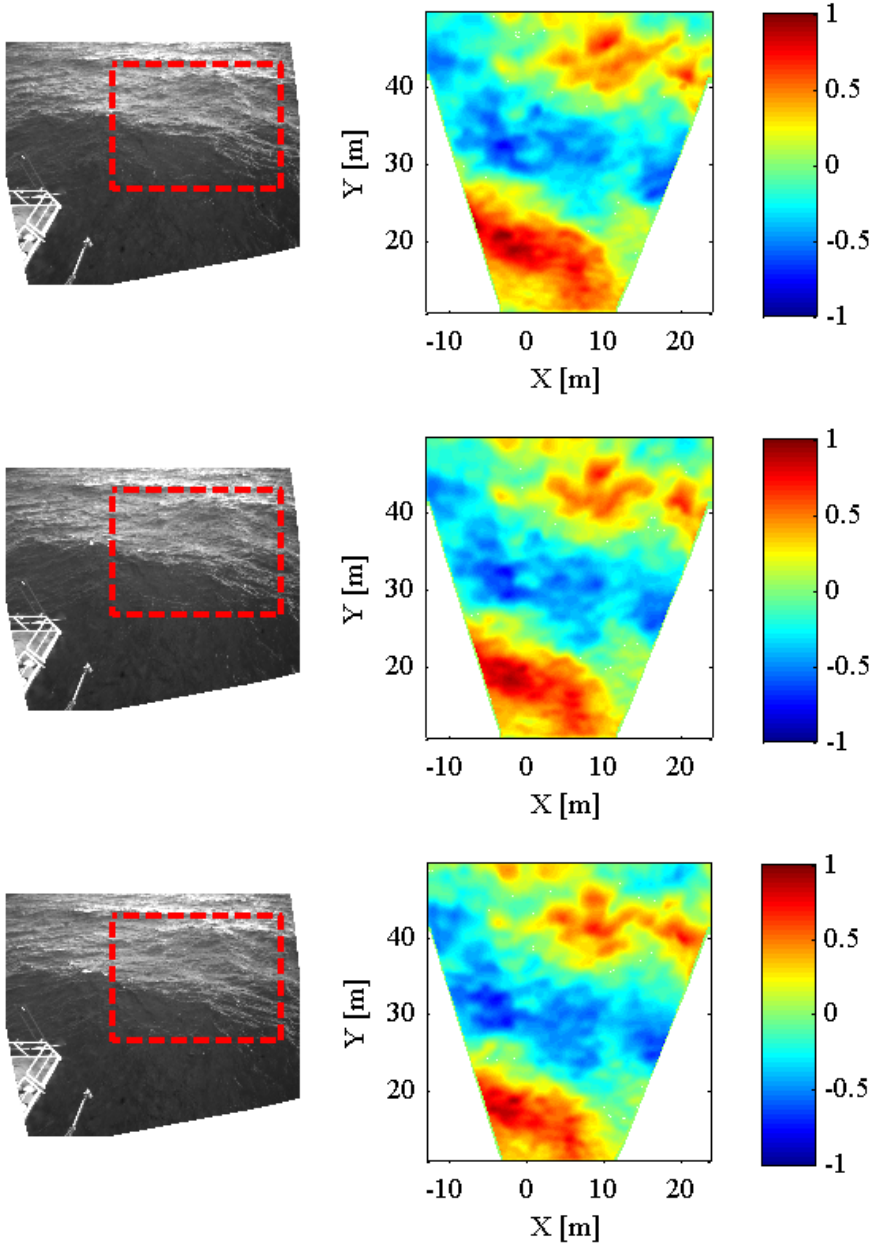


Reconstructed, scattered 3-D points.
At most: 1-D coherence.

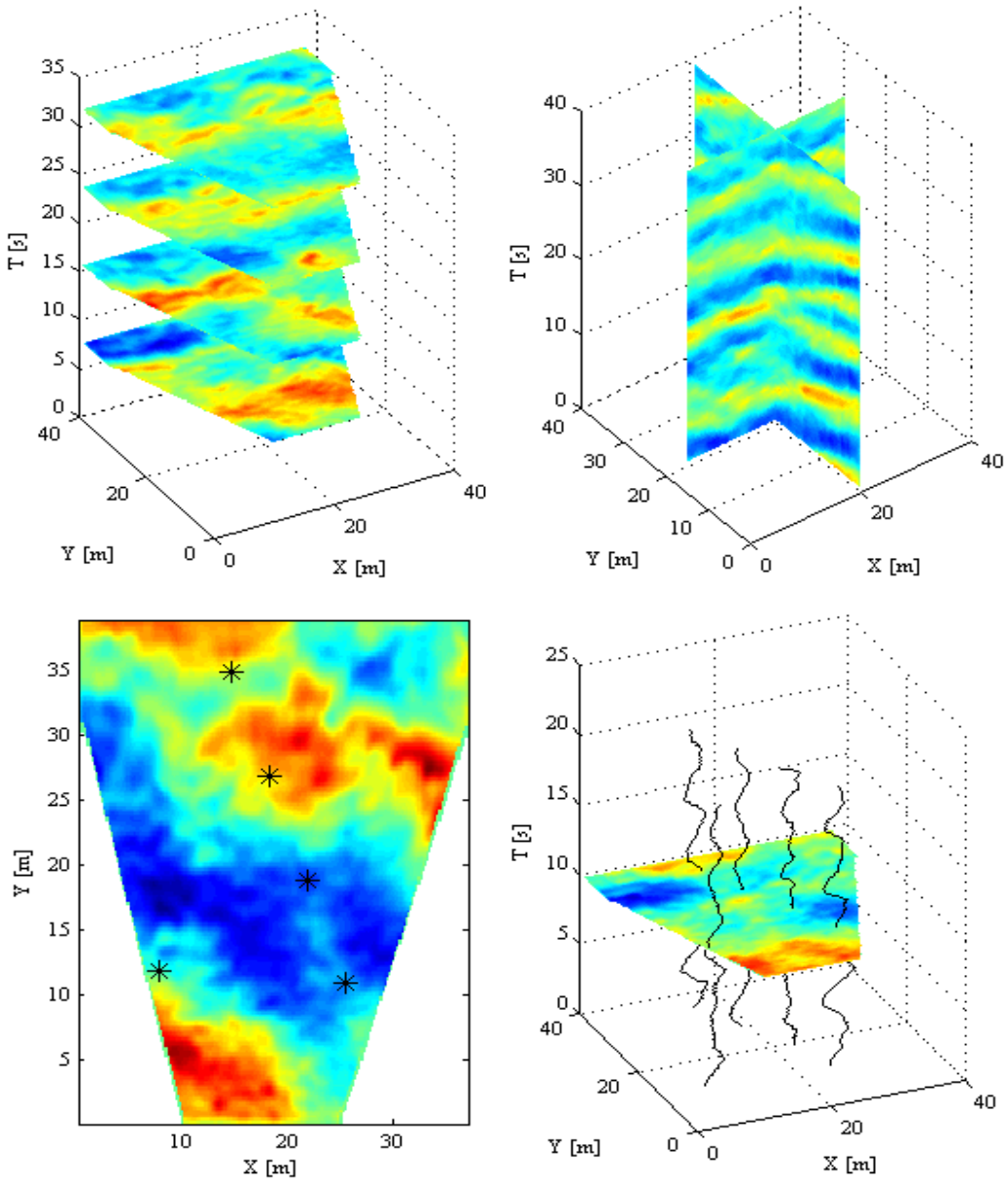


Plane fitting and outlier rejection

Epipolar method. Sequential processing

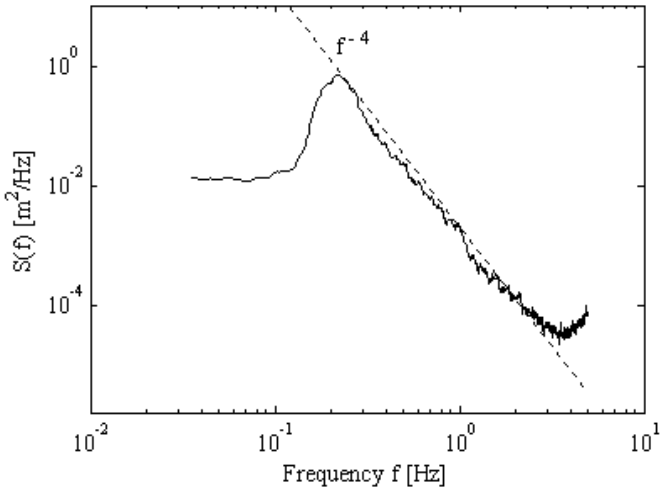


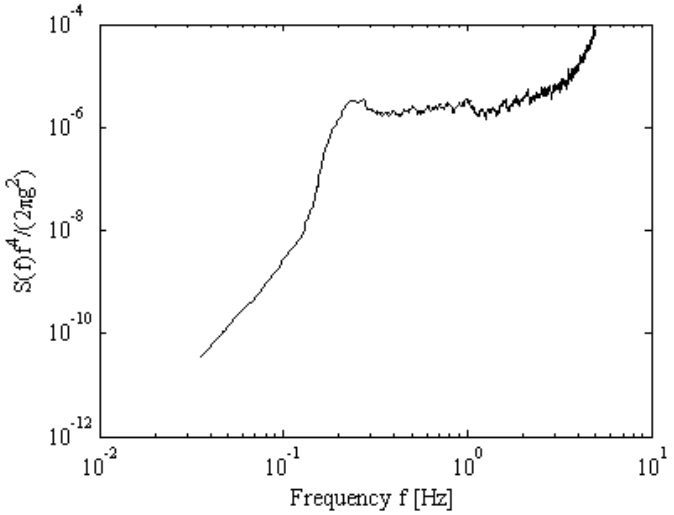
Epipolar method. 4D space-time wave volume



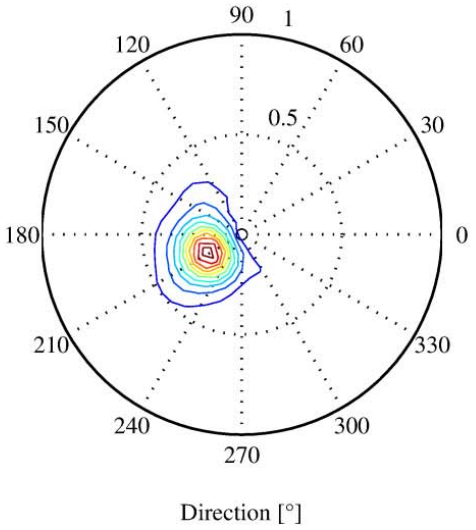
Epipolar method. Data analysis. Spectra

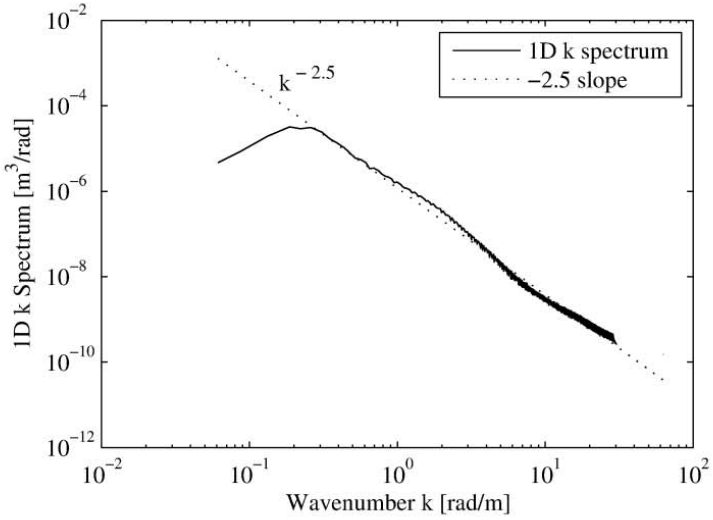
From time series at virtual probe points:



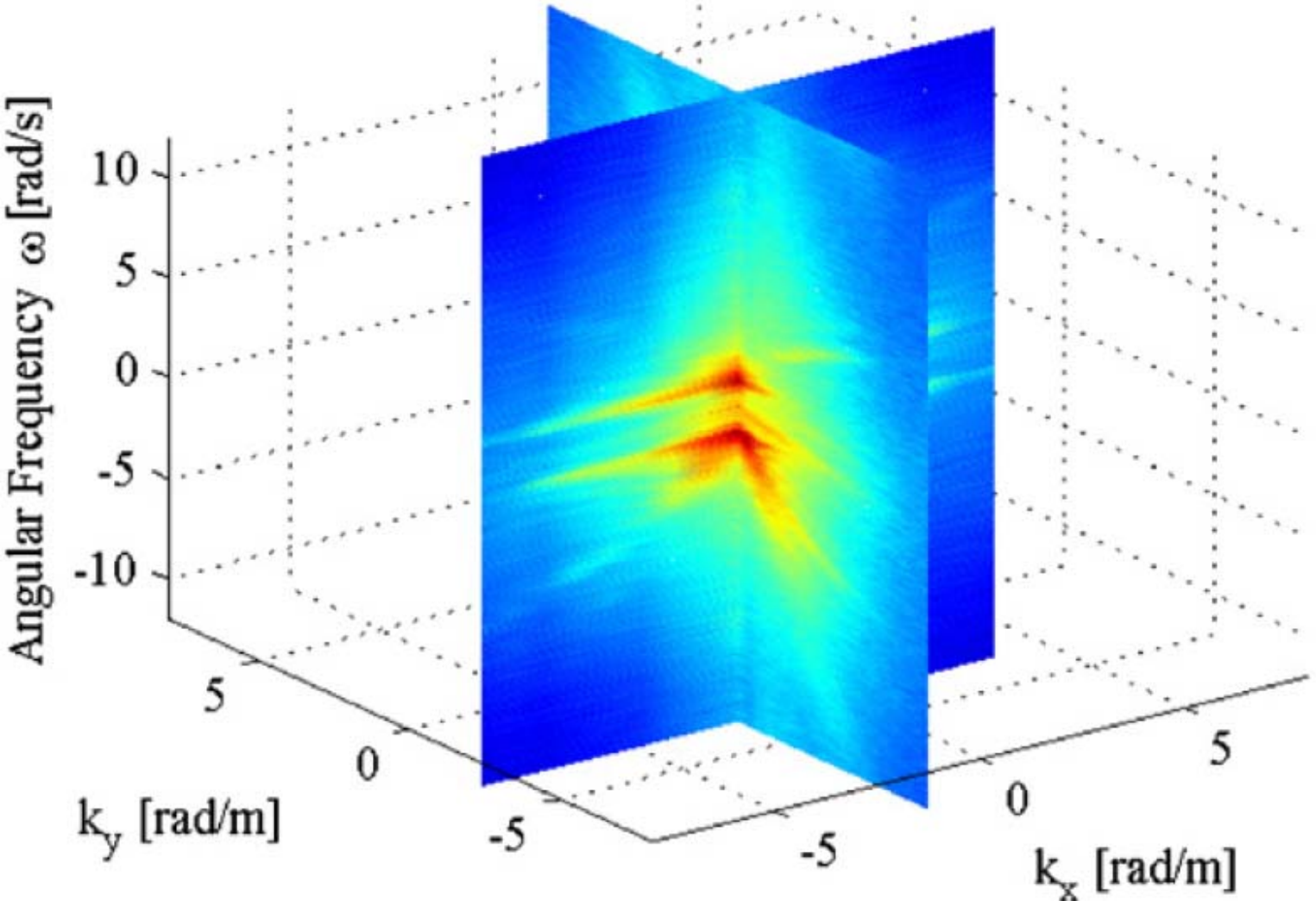


From 2-D snapshots. Directional and omni-directional spectra.



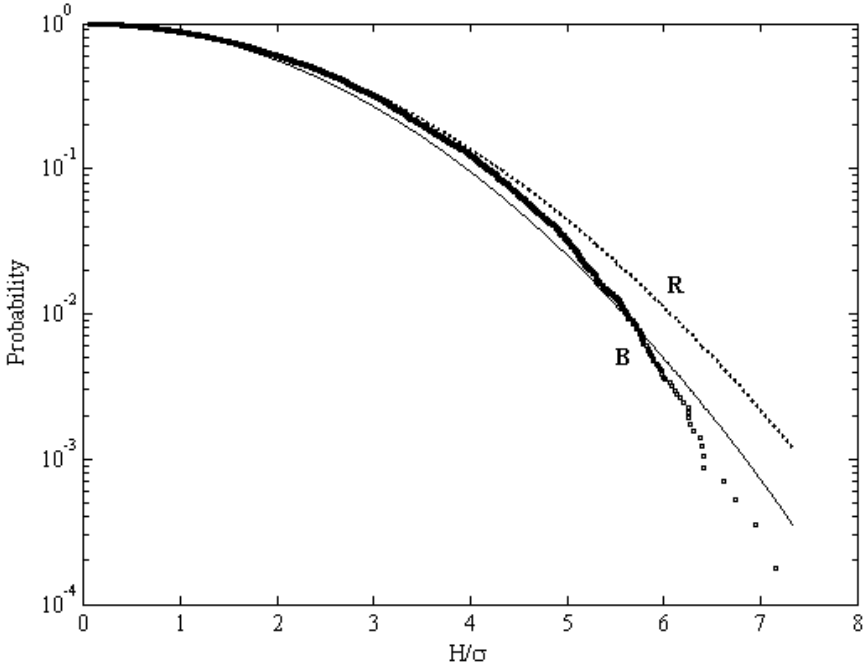


Epipolar method. Data analysis. 3D spectrum

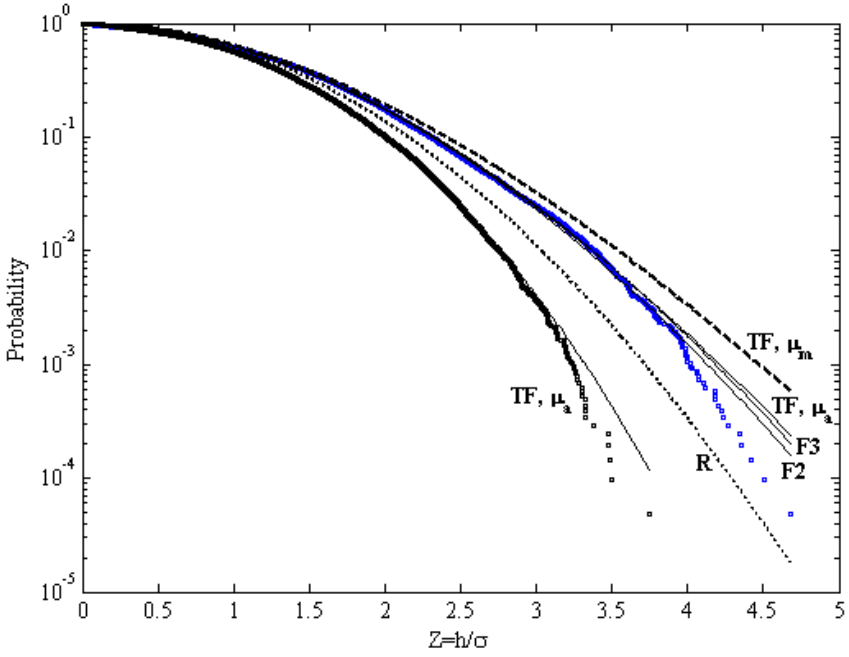


Epipolar method. Data analysis. Statistics

Wave height exceedance probability.

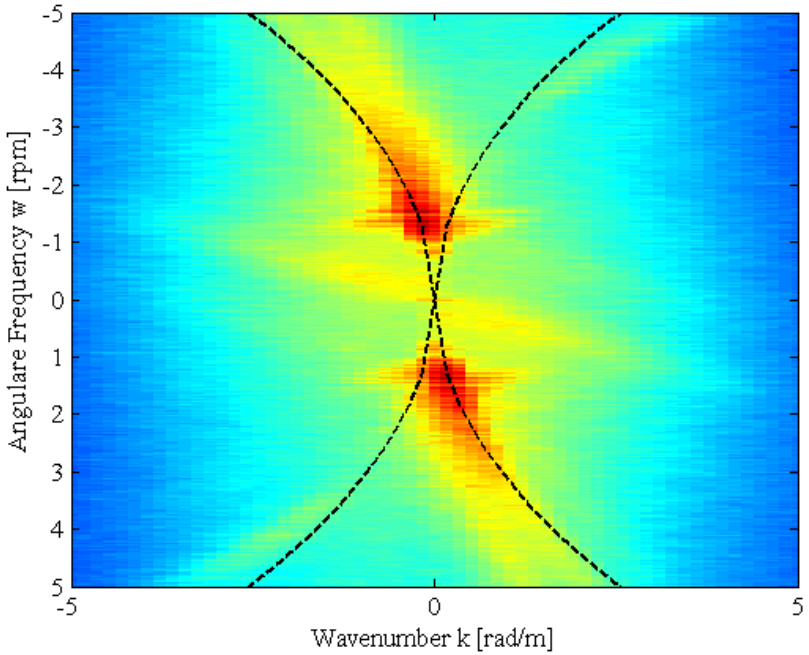


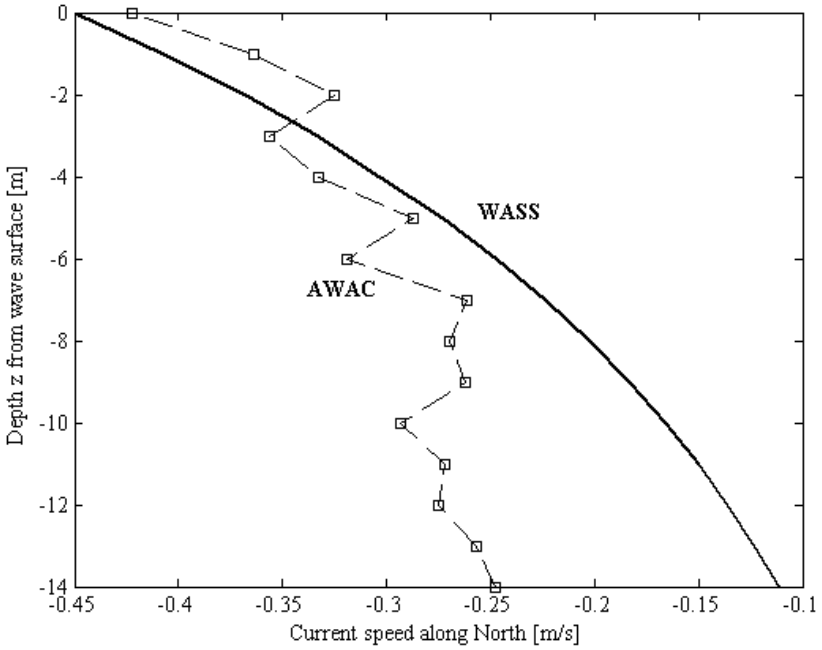
Wave crests and troughs exceedance probability



Epipolar method. Estimation of currents

Analysis of the deformation of the linear dispersion manifold to estimate currents





Epipolar method

Problem solved?

Epipolar method

Problem solved?

Some disadvantages:

- Sensitive to image noise.
- Correspondences are not easy to find.
- Unmatched regions: gaps in the surface.
- Requires strongly textured surfaces.
- Each point is treated independently (does not exploit continuity of surface).
- Post-processing is required.

How do we work around it?

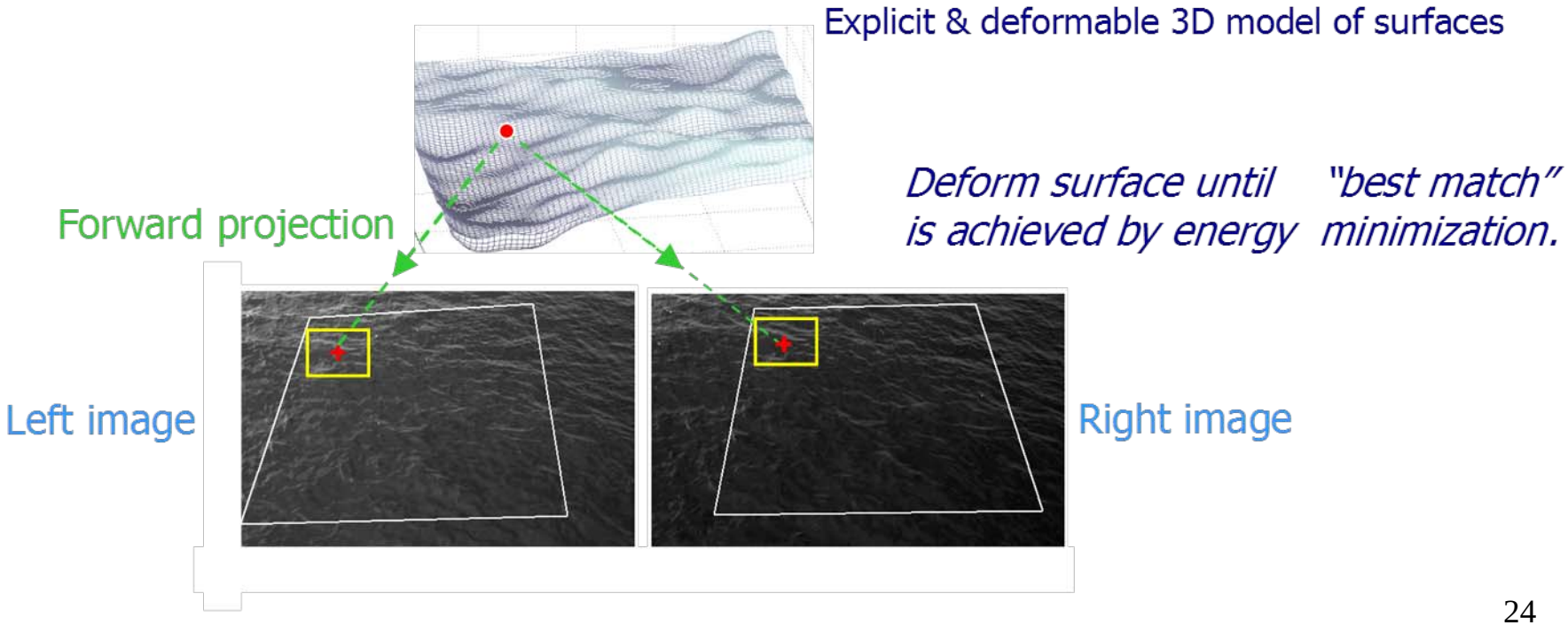
Advantages of variational methods

- Solid mathematical framework.
- Coherence, continuity of the wave surface.
- Robustness.
- Regularization, controllability.
- Less post-processing required.

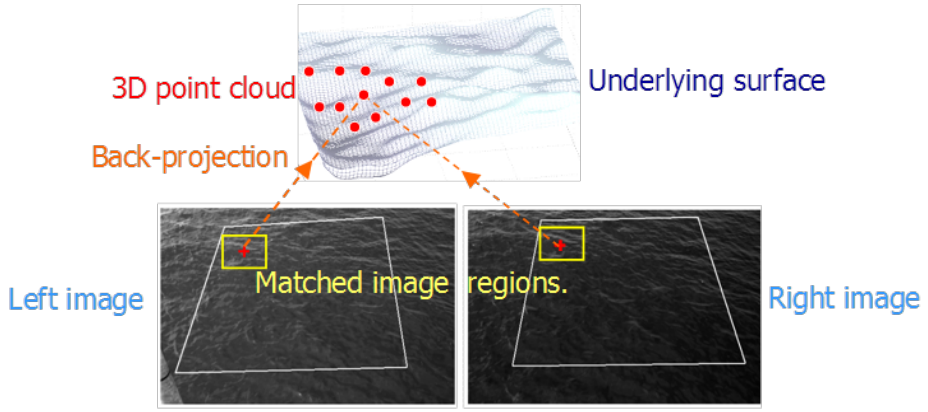
3-D reconstruction of the water surface from images

Variational stereo solution (Object-based methods)

Philosophy: adjust a 3D model to the 3D world represented by the data (images) so that an energy is minimized.



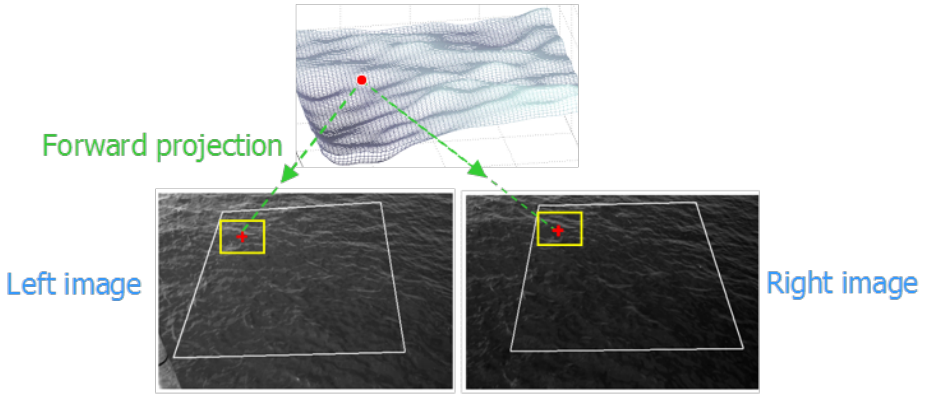
Classical stereo solution



- **Pros:**
  - Simplicity, implementation
  - Speed

- **Cons:**
  - Sensitive to noise
  - Correspondences are not easy to find
  - Unmatched regions: holes in the surface
  - Requires strongly textured surfaces
  - Each point is treated independently (does not exploit continuity of surface).

Variational solution



- **Pros:**
  - Solid mathematical framework
  - Can handle objects with mild textures (water)
  - Continuous model: smooth surface. No gaps
  - Less sensitive to noise
  - Can incorporate physics of the waves

- **Cons:**
  - Computationally expensive
  - More mathematically involved: PDEs, etc.

Variational algorithm

Graph representation: $S(u,v) = \big(u, v, Z(u,v)\big)$

Design a **cost functional** to be minimized:

- Joint estimation of height Z(u,v) or the waves and its radiance f(u,v)

Cost: $E(S,f) = E_{\text{data}}(S,f) + \alpha E_{\text{geom}}(S) + \beta E_{\text{rad}}(f), \qquad \alpha, \beta > 0.$

Data fidelity term: $E_{\text{data}} = \sum_{i=1}^{N_c} E_i$ **where** $E_i = \int_{\Omega_i} \phi_i \, \mathrm{d}\mathbf{x}_i, \quad \phi_i = \frac{1}{2}\big(I_i(\mathbf{x}_i) - f(\mathbf{x}_i)\big)^2.$

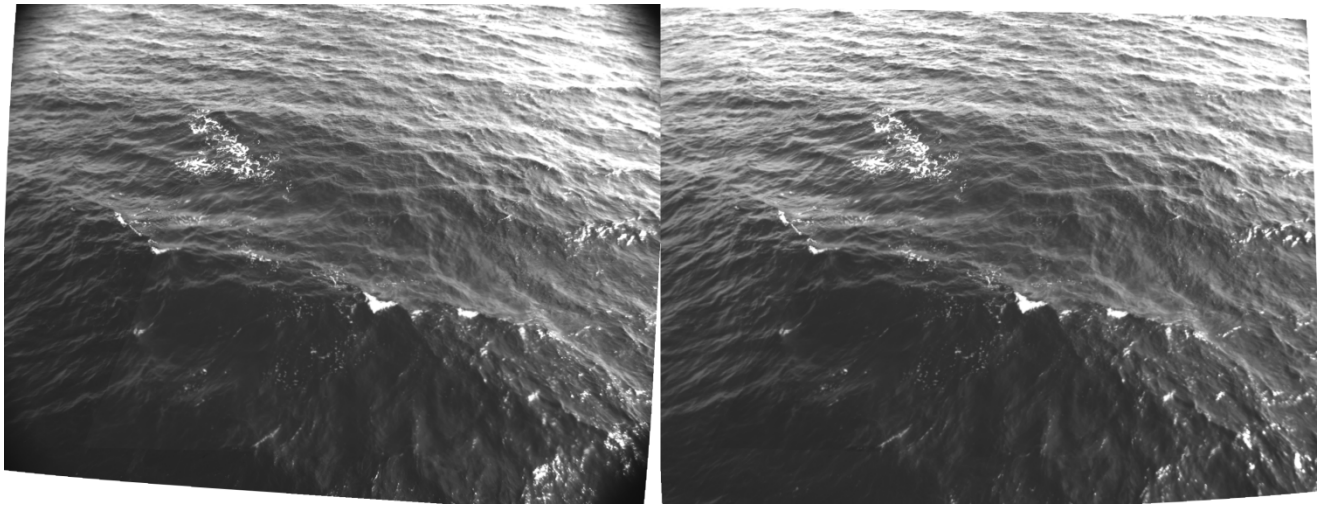
Regularizers: penalize the norm of the gradients of the height and the radiance

Cost as a function of height and radiance

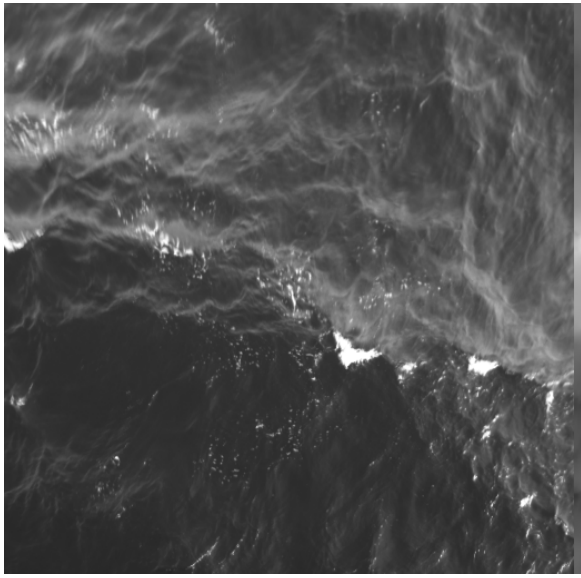
$$E(Z,f) = \int_U L(Z, Z_u, Z_v, f, f_u, f_v, u, v)\, \mathrm{d}\mathbf{u}.$$ ⇒ **Euler-Lagrange equations** ⇒ **Multigrid solver**

Variational algorithm

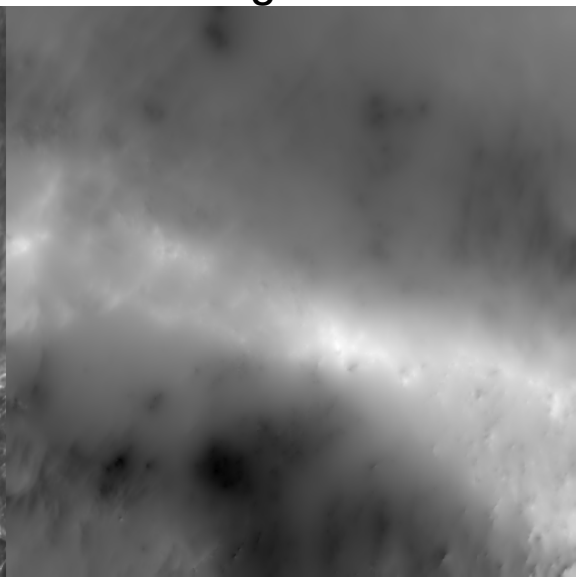
Modeled images



Radiance f

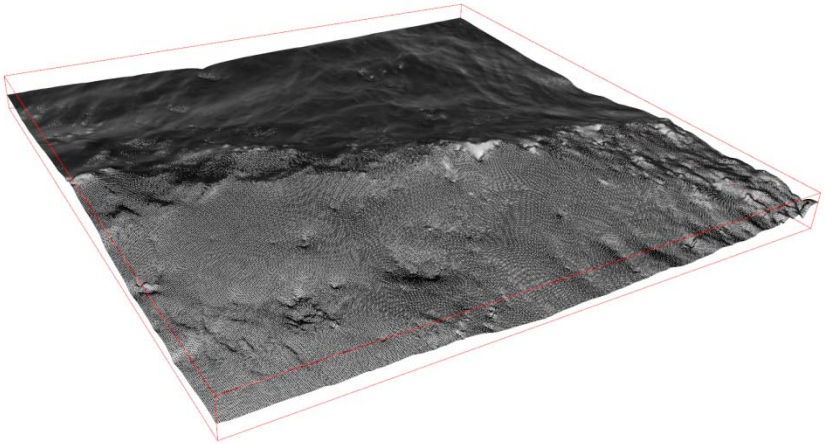


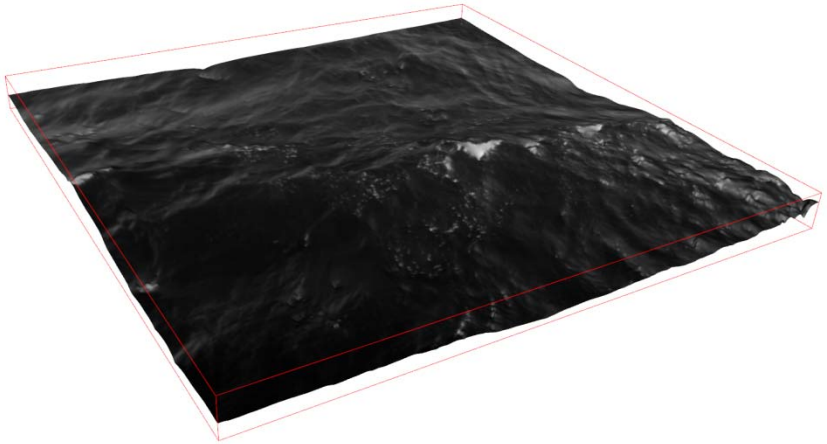
Height Z



Variational algorithm

Reconstructed surface

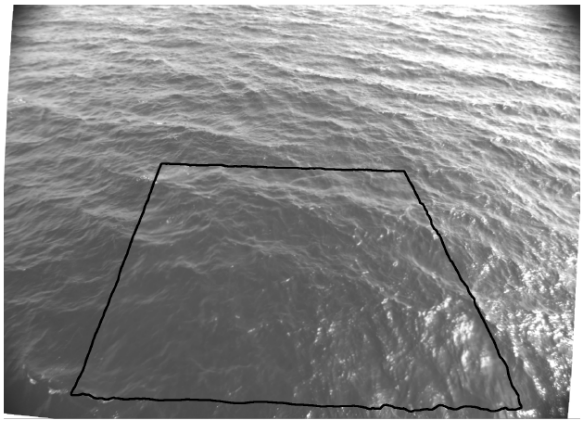




Sequential processing. Space-time wave volume

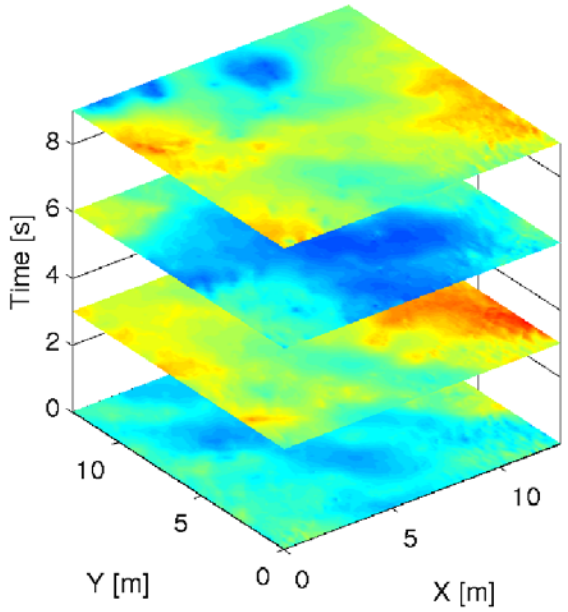
Input stereo video:

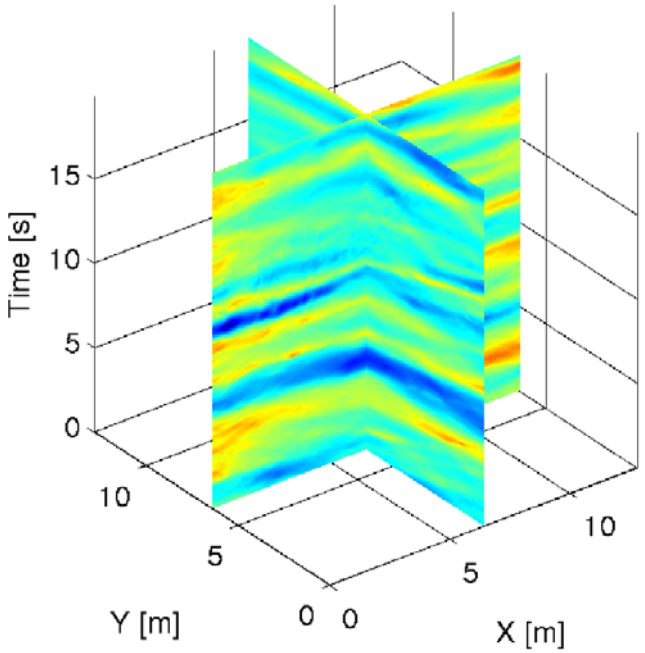
- Two cameras at Crimean platform
- Input images: 1624 x 1236 pixels.
- # snapshots: 28760 (~48 min)
- Frame rate: 10 Hz



Reconstruction:

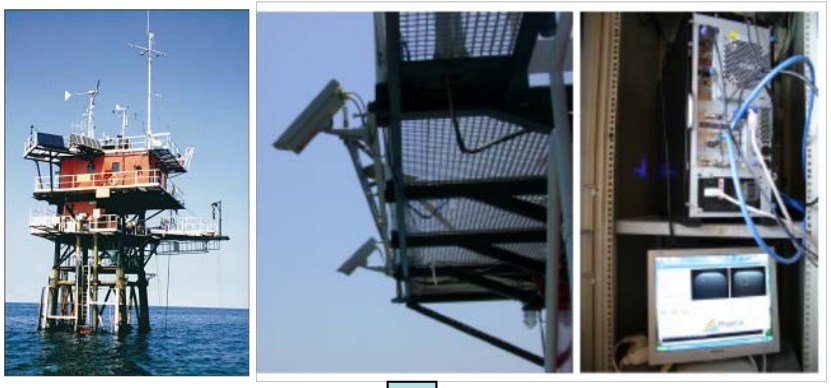
- Computational grid: 513 x 513 points
- Spatial resolution: 2.5 cm
- Reconstructed area: 12.8 x 12.8 m^2
- # snapshots processed: 6000 (10 min)



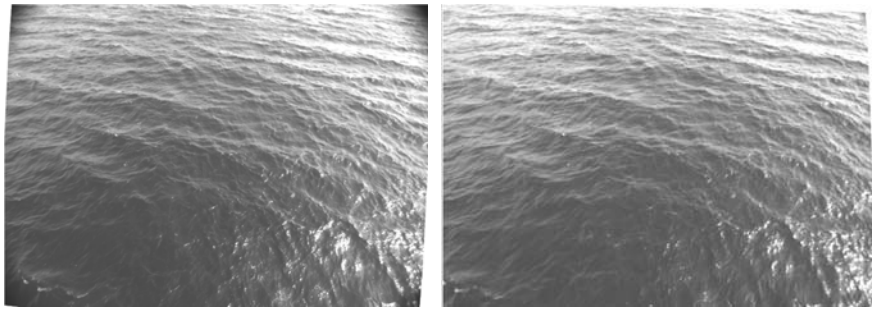


Video of the reconstruction

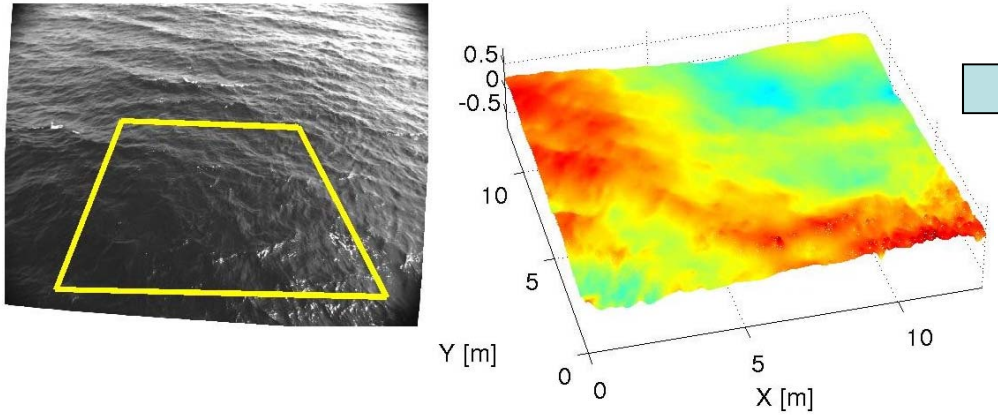
Platform: camera setup. Acquisition system (storing, syncronization, calibration, etc.)



Acquired images

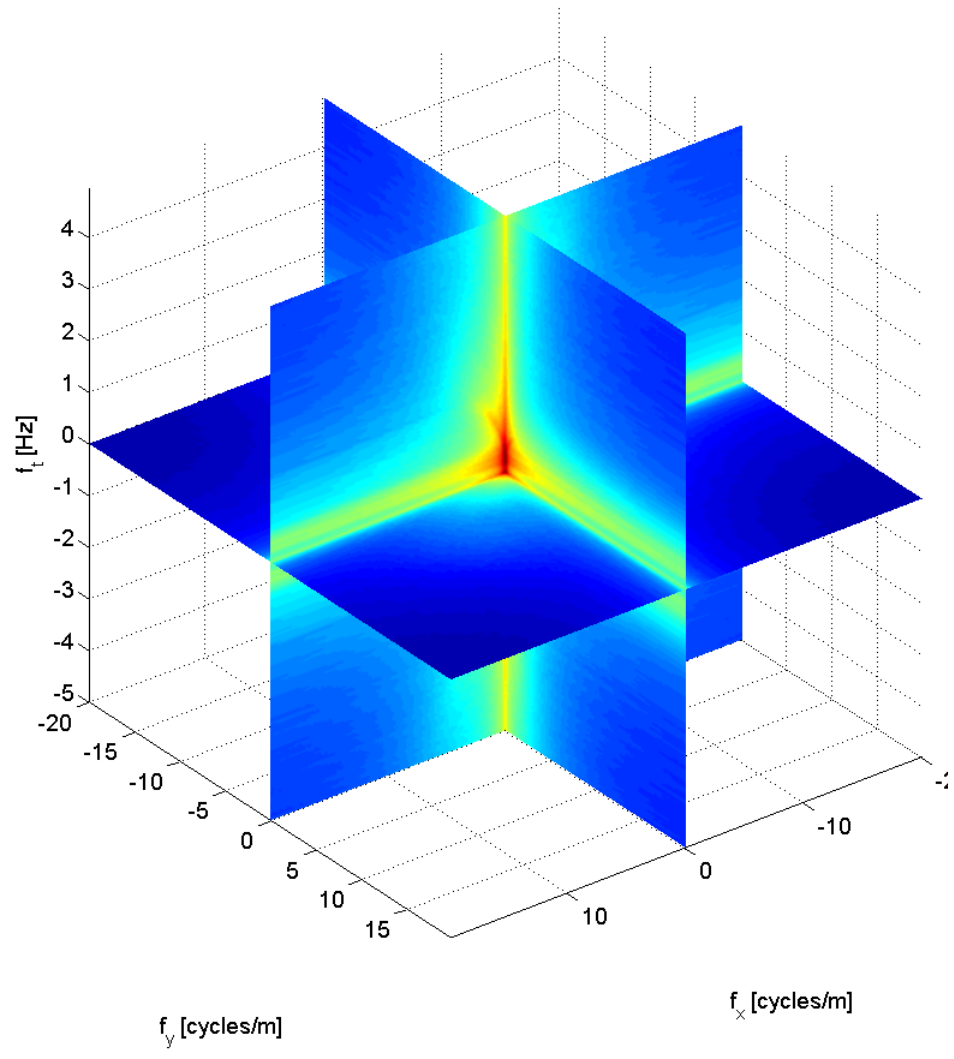


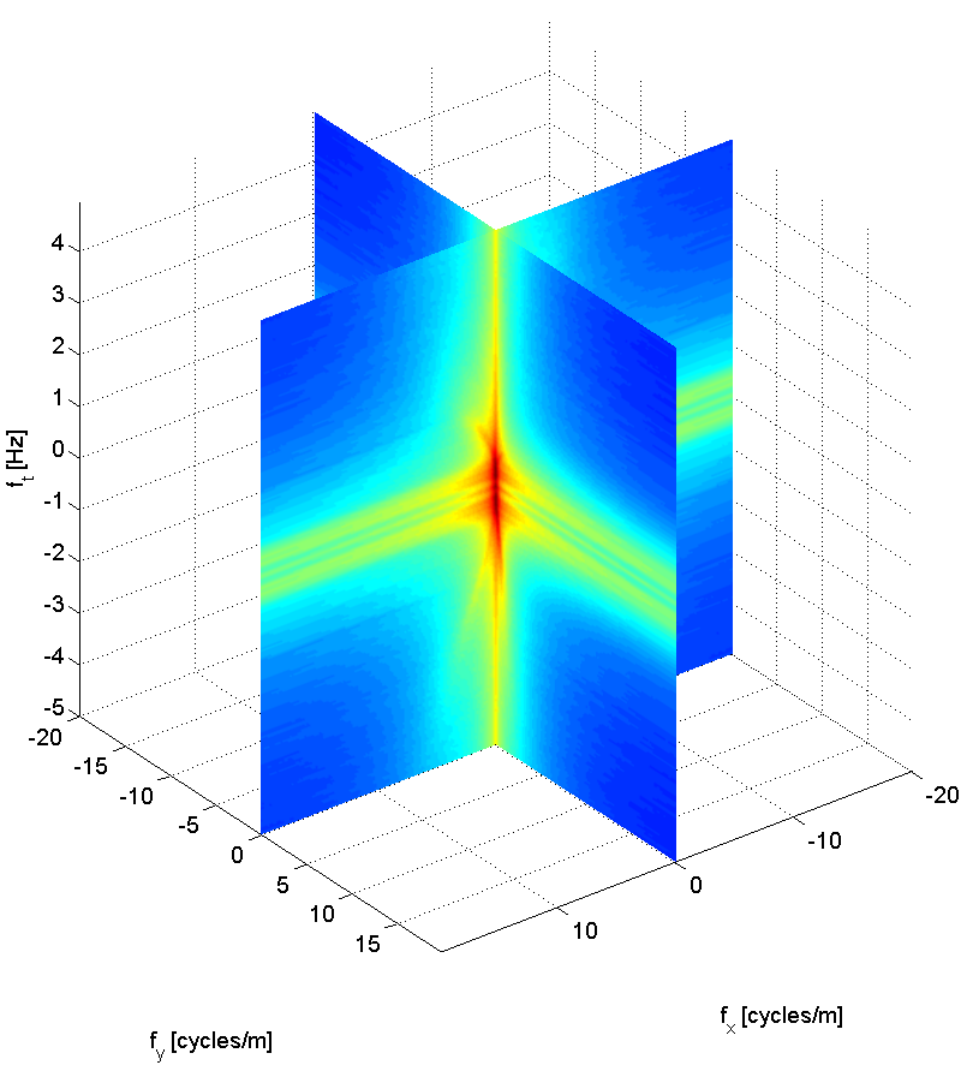
3D reconstruction of surface shape



Data analysis (statistics, spectra)

Average 3-D spectrum





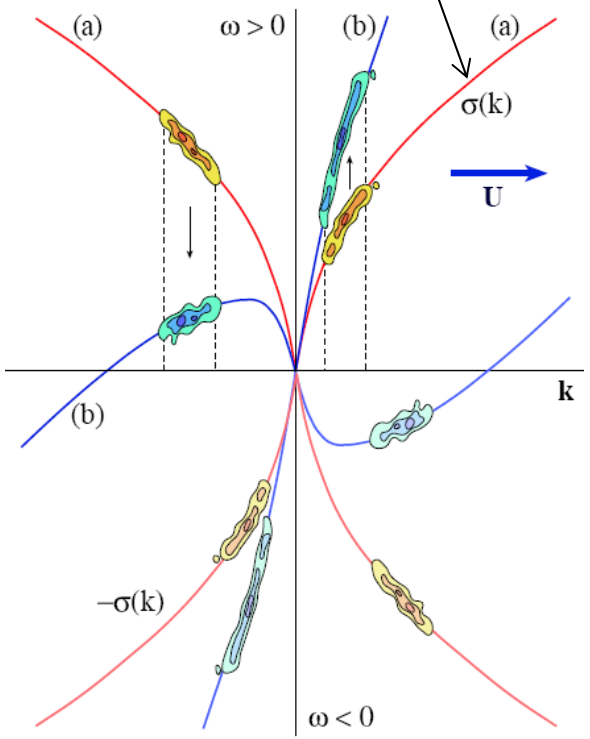
Crimea sequence. Input: 513x513x6000. Output: 512x512x512

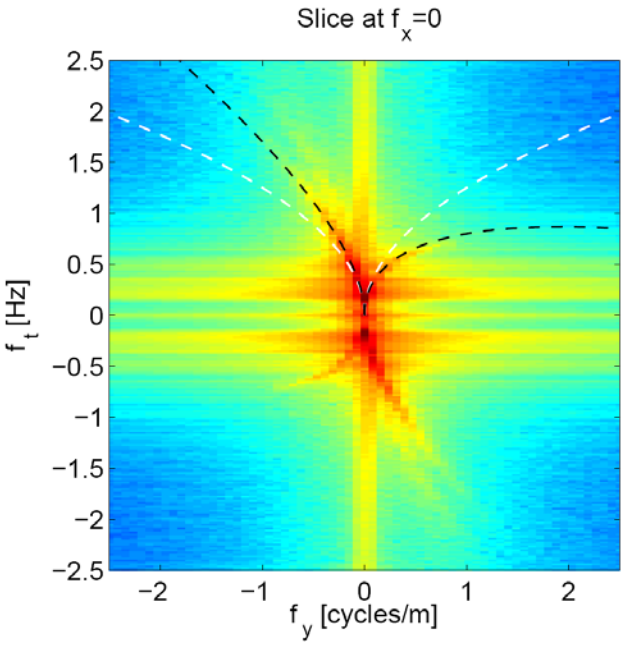
Average 3-D spectrum. Slicing

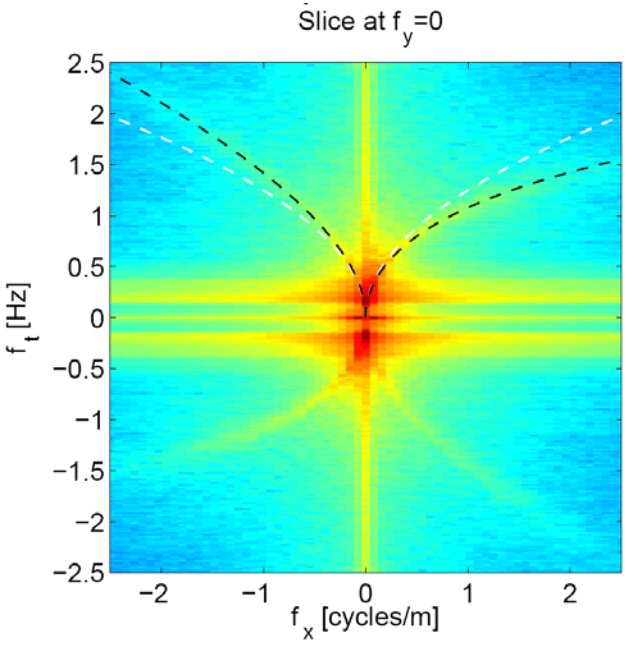
Taking into account the effect of surface currents:

Linear dispersion (in deep water)

$$k = \frac{\omega^2}{g}$$



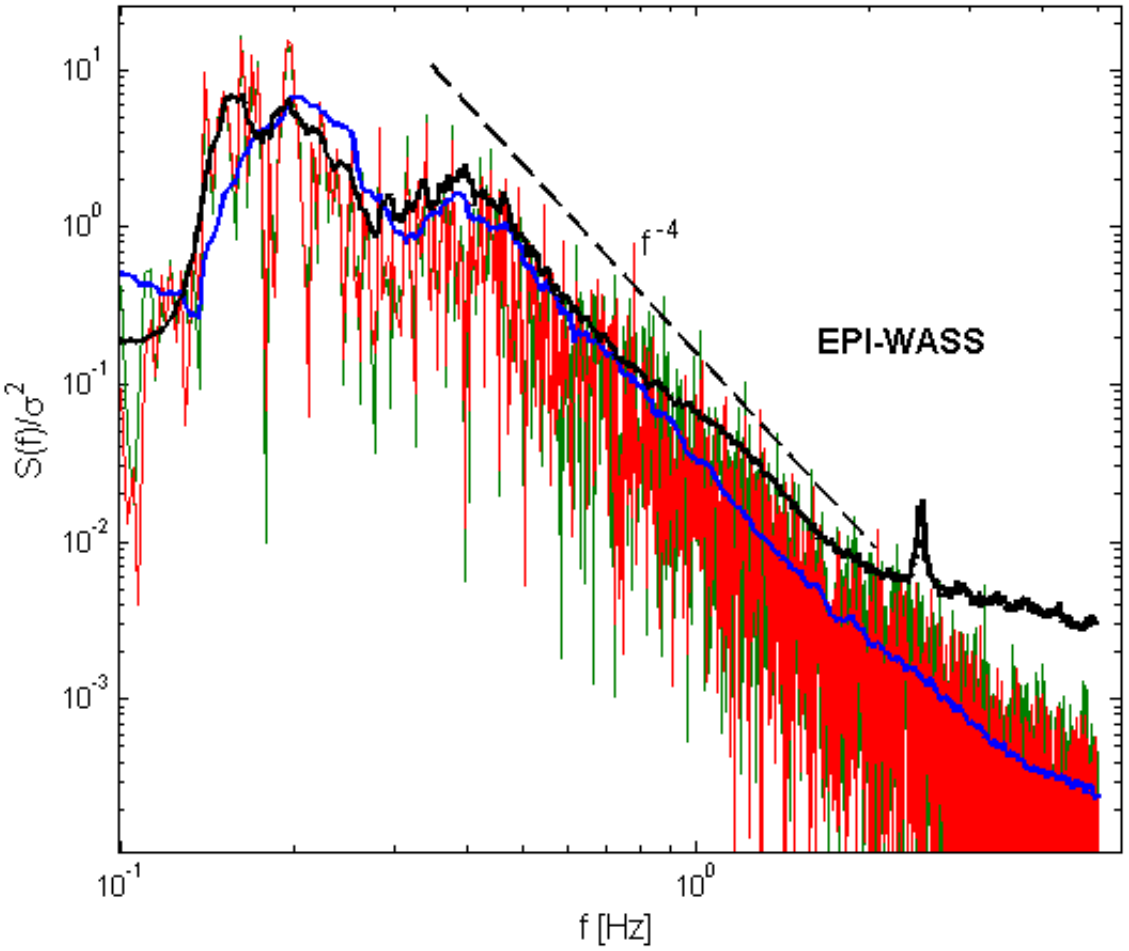




Velocity vector: u = (-0.17,-0.45) m/s

WISE poster: Nieto-Borges et al.

Comparison: Variational vs Classical Epipolar

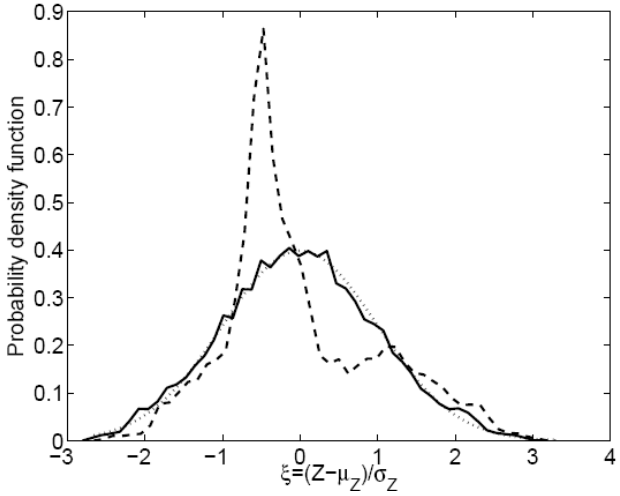


Reconstruct & enforce statistical constraints

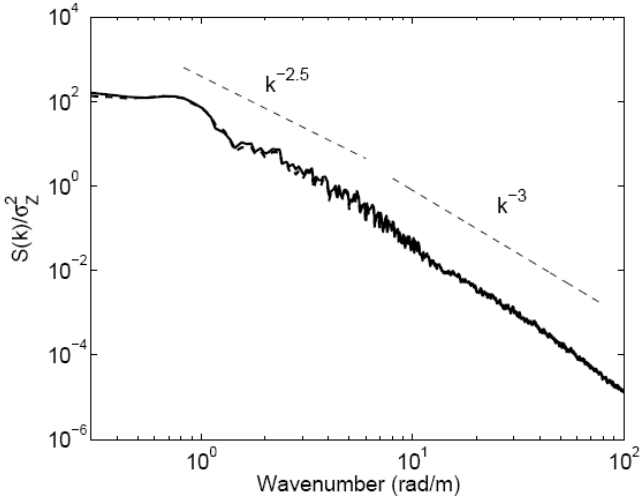
Add a cost penalty to measure statistical wave height distribution error:

$$E_{\text{stat}} := \int_{-\infty}^{\infty} w(z)\tfrac{1}{2}\left(G(z) - \text{cdf}^{Z}(z)\right)^2 dz$$

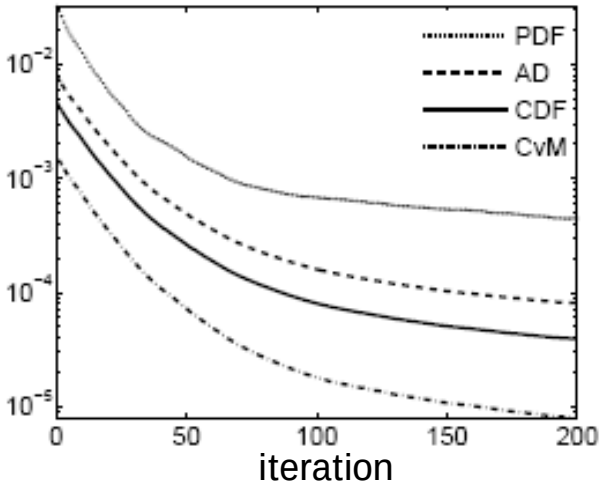
PDFs



Omnidir spectrum

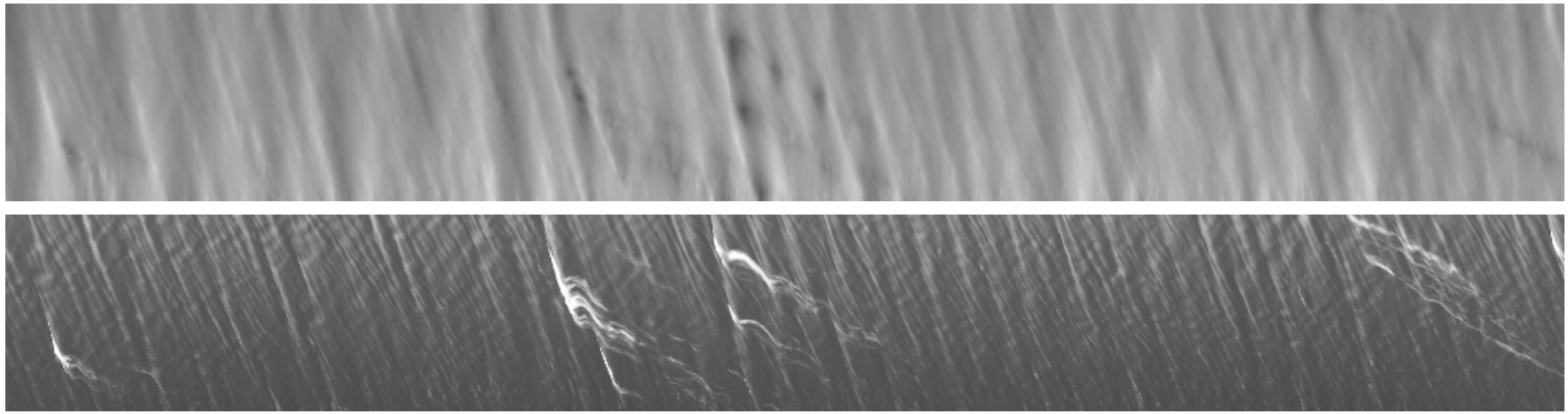


Cost evolution

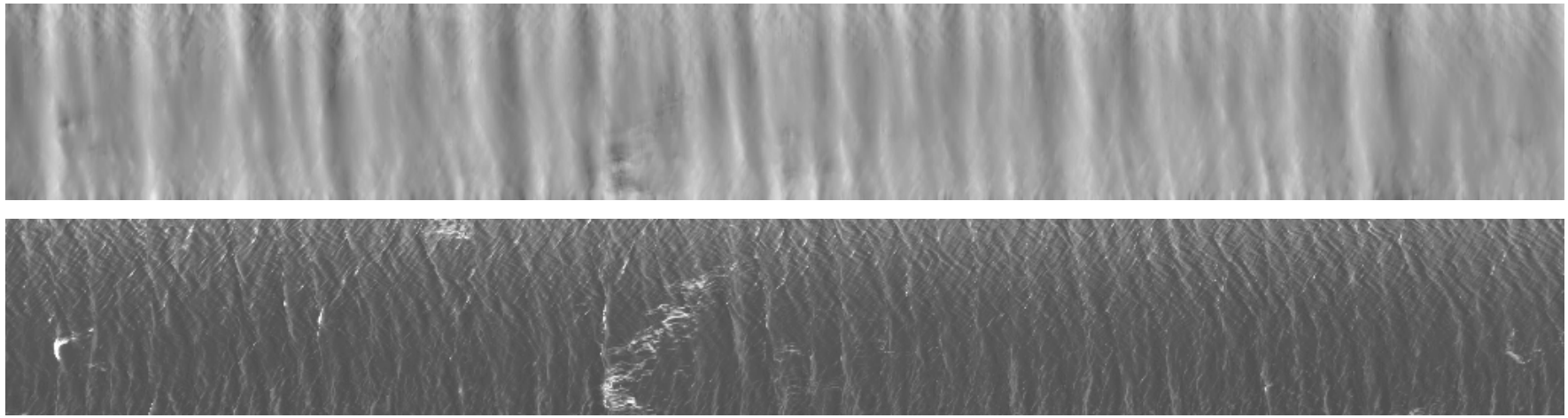


Simultaneous snapshot reconstr. Time coherence

1025 snapshots (100 s). Subsampled dataset (x4)



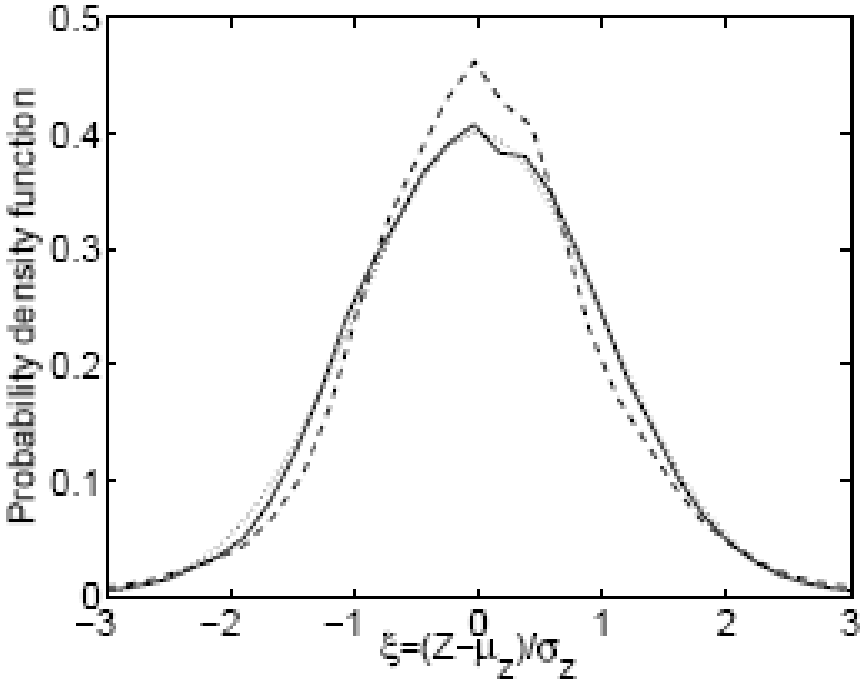
Time



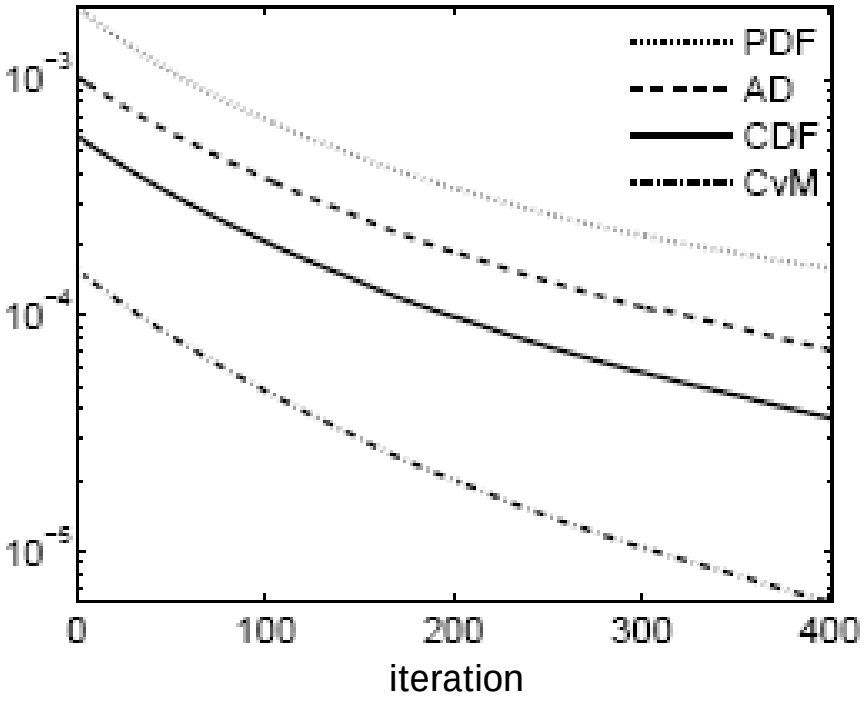
Time

Simultaneous reconstruct & statistical constraints

PDFs



Cost evolution



Conclusions

- Stereo reconstruction methods have more advantages than classical wave measurements (area vs. point measurements).

- Stereo methods provide reliable statistics and accurate predictions of ocean waves due to the rich information content of video data. They provide estimation of currents, wave parameters, maximum expected height over an area, etc.

Conclusions

- Stereo reconstruction methods have more advantages than classical wave measurements (area vs. point measurements).

- Stereo methods provide reliable statistics and accurate predictions of ocean waves due to the rich information content of video data. They provide estimation of currents, wave parameters, maximum expected height over an area, etc.

- Advantages of variational over epipolar method:
  - **Simultaneous reconstruction** of multiple snapshots is more robust: it enforces time continuity.
  - Variational framework can incorporate the **physics of the waves** (e.g. statistical constraints).
  - Requires **less post-processing**.

References:

- Benetazzo, A., 2006. Measurements of short water waves using stereo matched image sequences. **Coastal Engineering** 53, 1013–1032.
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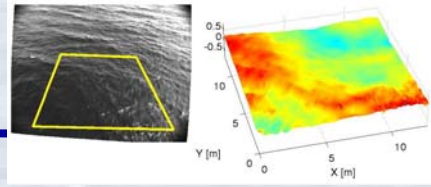
- A. Benetazzo, F. Fedele, G. Gallego, P.-C. Shih, A. Yezzi, Offshore stereo measurements of gravity waves, **Coastal Engineering**, Volume 64, June 2012, Pages 127-138.
- Gallego, G., Yezzi, A., Fedele, F., Benetazzo, A., Weak Statistical Constraints for Variational Stereo Imaging of Oceanic Waves. SSVM 2011. **Lecture Notes in Computer Science**, 2012, Volume 6667/2012, 520-531.

Acknowledgements:



Luigi Cavaleri
Crimea Data from Dr. Ardhuin.

THANK YOU FOR YOUR ATTENTION.

ANY QUESTIONS ?

More information:

http://www.gti.sssr.upm.es/~ggb/

http://savannah.gatech.edu/people/ffedele/Research/